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SUBJECT: Mechanical and Electrical Reliability Models for Major Rehabilitation Evaluation Reports

CATEGORY: Guidance

1. **References:**

a. Definition of Rehabilitation for Inland Waterway Projects, Public Law 102-580 (WRDA 1992), 33 USC 2327, Section 205, 31 Oct 1992

b. Engineering Regulation (ER) 1130-2-500 Project Operations Partners and Support Work Management Guidance and Procedures, 27 Dec 1996.

c. Engineer Pamphlet (EP) 1130-2-500 Project Operations Partners and Support Work Management Guidance and Procedures, 27 Dec 1996.

d. Engineering Circular (EC) 1110-2-6062 Risk and Reliability Engineering for Major Rehabilitation Studies 1 Feb 2011.

e. Patev, R.C., Buccini, D.L., Bartek, J.W., and Foltz, S. 2013. Improved Reliability Models for Mechanical and Electrical Components at Navigation Lock and Dam and Flood Risk Management Facilities. ERDC/CERL Technical Report 13-4, Vicksburg, MS. https://usace.contentdm.oclc.org/digital/collection/p266001coll1/id/4332/

f. Hartford, D., Baecher, G.B., Zielinski, P.A., Patev, R.C., Ascilia, R and Rytters, K.2016. Operational Safety for Dams and Reservoirs. ICE Publishing, London, UK. https://www.icevirtuallibrary.com/isbn/9780727761217?mobileUi=0

g. USACE Asset Management Data – Operational Condition Assessment Weibull tables https://assetmanagement.usace.army.mil

2. **Purpose.** This Engineering and Construction Bulletin (ECB) provides guidance for mechanical and electrical reliability models developed for Major Rehabilitation Evaluation Reports (MRER). These reliability models are necessary for an MRER economic analysis. ER 1130-2-500 and EP 1110-2-500 provide requirements for the overall Major Rehabilitation program.

3. **Background.**

a. Previous US Army Corps of Engineers (USACE) guidance on mechanical and electrical reliability has expired. The use of Fault Tree Analysis (FTA) has become the standard tool for mechanical and electrical systems analyzed in an MRER. Previous guidance was given in EC 1110-2-6062. This EC is in the process of being converted to an engineering manual. The purpose of this ECB is to provide interim guidance for MRER development while EC 1110-2-6062 is being updated.

b. FTA models are a top-down approach that start by defining the limit state and work down to identify components whose failure would result in realization of the limit state. To obtain good results from these FTA models, failure distributions are required for each component at the bottom level of the fault tree.

c. The failure distribution used in most USACE FTA is the Weibull distribution since it can best represent the common distributions (exponential, normal, lognormal, etc.) found with USACE mechanical and electrical failure datasets. The Weibull distribution is either a two parameter (alpha and beta) or a three parameter (alpha, beta, and gamma) analysis. The alpha parameter represents the characteristic life (CL) in years, which is defined as the age at which 63.2% of like components under identical conditions will have failed. Beta is the shape parameter of the distribution (e.g. normal distribution is a beta of about 4) and gamma is a shift of the start of the Weibull distribution. The commonly used units for alpha and gamma are years, but the units of these parameters will be equivalent to those for the independent variable of the failure distribution.

d. Current USACE practice of using alpha adjustments and gamma shifts for the Weibull distribution in fault trees or reliability block diagrams models was leading to unreasonable Weibull parameters and life distribution for an expected mean time to failure (MTTF). In addition, these models generally did not include methods to represent differences in environment, loading, and schedule of operation of like components at different projects. Methods to account for these factors were included in previous expired MRER guidance to account for actual operational use of mechanical and electrical components at a project.

4. **Applicability.** This ECB applies to USACE Civil Works projects when developing fault tree or reliability block diagrams for an MRER. USACE has two options for FTA software on the USACE APP portal (https://app-portal.usace.army.mil/ESD). This includes Reliability Workbench (RWB) and Availability Workbench (AWB). Reliability Workbench is primarily used for safety analysis of systems to estimate the on-demand failure probability for the top event or any subsystem in the fault tree. RWB should be used for FTA in the USACE dam and levee safety program. For MRER development, AWB should be utilized since it can account for a proper duty factor, environment factor and load factors that reflect actual operational conditions experienced by mechanical and electrical components at a project.

5. **Guidance.**

a. Selection of Weibull Parameters for Fault Tree and Reliability Block Diagrams**.** The guidance provided in the attachments applies to models that utilize Weibull parameters in the reliability models for MRER. This guidance recommends values of the Weibull parameters, alpha and beta, for navigation (NAV) and flood risk management (FRM) projects and outlines some possible methods for manual estimation of Weibull parameters in the absence of data. This data is summarized from three USACE resources.

1. ERDC Technical Report 13-4 (NAV and FRM). This report developed the use of Expert-Opinion Elicitation (EOE) to help estimate the characteristic life (CL) of mechanical and electrical components at USACE navigation projects. This report estimated the CL (Weibull alpha parameter) for mechanical components at both navigation (NAV) and flood risk management (FRM) projects and electrical components at NAV only. See details in Attachment A.

2. Operation Safety of Dams and Reservoirs (FRM). Weibull data is found in Appendix A of this OSDR book and contains failure data collected from 295 USACE FRM projects in 2011. See Attachment A for more details.

3. Asset Management Operational Condition Assessment (NAV and FRM). These resources will be covered in more detail with recommended tables for Weibull parameters in Attachment A.

4. Manual estimation of Weibull parameters. There are many methods to derive Weibull parameters manually. Some of these methods are outlined in Attachment A.

b. Duty and Environmental/Load Factors. This attachment addresses how to apply duty and environmental load factors to the components in the AWB fault tree model. Recommended values and considerations are available in tables shown in Attachment B.

c. Application Example to Fault Tree and Reliability Block Diagrams in Availability Workbench**.** An example of a Dam Gate Operating Equipment FTA is provided in Attachment C to show the step-by-step application of this guidance to an AWB fault tree model. For guidance for AWB FTA model development and Weibull probability plotting, refer to Attachment C.

6. **Date of Applicability.** This ECB is effective immediately.

7. **Point of Contact.** HQUSACE point of contact for this ECB is Timothy M. Paulus, P.E., CECW-EC, (651) 528-9457.

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Enclosures:
Attachment A – Weibull Parameter Data Sources and Methods
Attachment B – Duty and Environmental/Load Factors
Attachment C – Application Example

ATTACHMENT A: Weibull Parameter Data Sources and Methods

Currently there are three data sources available for Weibull parameters for USACE components at navigation locks and dams and flood risk management dam safety projects. These three data sources are:

1. **ERDC/CERL Technical Report 13-4 (Patev et al 2013).** This report used Expert Opinion Elicitation to estimate the Characteristic Life (CL) (Weibull alpha parameter) for mechanical components at both navigation (NAV) and flood risk management (FRM) projects and electrical components at NAV only.

   It is recommended that this is the first choice for CL data for components in FTA for MRERs. Values for the Weibull beta (shape parameter) were not elicited as part of this study. The Weibull beta value reflects the different stages in a part's life that it is expected to fail. Beta values less than 1 imply failures very early after installation or high "infant mortality". Beta values equal to 1 imply random failures, meaning that failures are independent of time. Beta values between 1 and 4 imply early wear out, and beta values greater than 4 implies old age (rapid) wear out. Most components in the USACE portfolio fail later in their life cycle due to wear out. Beta values between 3 and 4 are therefore recommended to reflect that failure characteristic. Summary Table A-1 (mechanical) and Table A-2 (electrical) are presented below.

Table A-1: CLs for Mechanical Components at NAV and FRM Projects from ERDC/CERL TR 13-4

Type	Component	Navigation Components CL (years)	Flood Reduction Components CL (years)
Bearings	Rolling Element	40	60
	Sleeve (self-lubricated)	25	20
	Bronze Sleeve	40	60
Couplings	Flexible	35	40
	Rigid	50	60
Shafts	Shaft	50	100
Pins	Pin	35	70
Gear Reducers	Worm	25	40
	Parallel	40	60
	Right Angle	38	40
Open Gearing	Spur	50	100
	Helical	38	100
	Bevel	40	50
	Rack	50	80
Brakes	Electromechanical	45	60
Clutches	Slip	30	-
	Jaw	-	70
Wire Ropes	Spiral Plate	5	-
	Single/Multiple Sheaves	20	-
	Single Drum	28	-
	Round	-	50
	Flat	-	20
Wire Rope Drums	Wire Rope Drum	50	100
Wire Rope Sheaves	Wire Rope Sheave	33	50
Chains	Roller	40	60
	Link	-	40

Type	**Component**	**Navigation Components CL (years)**	**Flood Reduction Components CL (years)**
Chain Sprockets	Chain Sprocket	60	75
Miter Gates	Sector Arms	73	-
	Strut Arms – Buffered	35	-
	Strut Arms – Rigid	40	-
	Support Roller	43	-
	Rack Support Beam	60	-
Culvert Valve Machinery	Bellcrank	78	-
	Crosshead/Guide	73	-
	Strut	43	-
Hydraulic Cylinders	Hydraulic Cylinder	60	60
Hydraulic Control Valves	Check	45	40
	Relief	40	40
	Manual	60	60
	Solenoid	40	40
	Proportional/Throttle	40	40
Pumps	Fixed Displacement	50	60
	Variable Displacement	30	35
Hydraulic Motors	Fixed	50	-
	Variable	30	-
Piping	Piping	40	40
	Hose	-	25
Misc Gate/Filling or Emptying Valve Components			
Wheel Assembly (Rollers)	Wheel Assembly	40	50
Pintles/Bushings	Pintles/Bushings	30	-
Gudgeon/Bushings	Gudgeon/Bushings	43	-
Trunnion Pin/Bushings	Trunnion Pin/Bushings	38	60
Strut Spindle Pins	Strut Spindle Pin	25	-
Other Systems			
Tow Haulage System	Hydraulic	30	-
	Mechanical	48	-
Emptying and Filling System	Butterfly	50	-
	Vertical Lift	50	-
Gate Connection (Pins, Cable, and Chain)	Gate Connection (Pins, Cable, and Chain)	-	50
Grease/Lubrication System	Grease/Lubrication System	-	30
Actuators (Screw Type, Limit Torque)	Actuators (Screw Type, Limit Torque)	-	50
FRM Water Control Valves	Butterfly	-	50
	Ball	-	50
	Slide	-	50
	Knife	-	50
	Jet	-	50

Table A-2: CLs for Electrical Components at NAV Projects from ERDC/CERL TR 13-4

Type	Component	Navigation Components CL (years)
Commercial Power	Power Utility	4
Service Transformers	Service Transformer	55
Transfer Switches	Automatic	30
	Manual	65
Switchgears	Switchgear	78
Circuit Breakers	Circuit Breaker	63
Power Panelboards	Power Panelboard	78
Cables	Buried/submerged	60
	Duct/cable tray	80
	Portable/flexible	28
Bus Ducts	Bus Duct	95
Switchboards	Switchboard	83
Motor Control Centers (MCCs)	Motor Control Center	83
Motor Starters	Full voltage	63
	Reduced/variable	50
	VFD	35
PLC Systems	PLC System	25
Selsyn Motors	Selsyn Motor	43
Limit Switches	Travelling Nut Limit Switch	65
Electric Motors	New or rebuilt Electric Motor	68
Standby Generator Sets	Standby Generator Set	50
DC Brake Rectifiers	DC Brake Rectifier	35

2. **Operational Safety of Dams and Reservoirs (OSDR) (Hartford et al 2016)**. Weibull data is found in Appendix A of this OSDR book and contains failure data collected from 295 USACE FRM projects in 2011. This Weibull data is shown using both a Weibull probability plotting method and a Bayesian updating method from the University of Maryland Center for Reliability Engineering. The Bayesian data is preferred since it accounts for those components that had both failed and those that had survived up to time, "t".

   It is recommended this data be used for FRM projects. Weibull data generated for NAV components may not be as accurate since that data is skewed to components that are not operated frequently. See Table A-3 (Mechanical) and Table A-4 (Electrical) below.

Table A-3: Weibull Parameters for Mechanical Components for USACE FRM Projects

Component	Total Inventoried	Weibull Plotting Method		Bayesian Method (Uniform Prior)	
		Characteristic Life: α	Shape Parameter: ß	Characteristic Life: α	Shape Parameter: ß
Air compressor	51	47.22	10.37	66.94	8.94
Bearings (bronze bushing type)	2014	74.96	6.751	81.93	7.29

Component	Total Inventoried	Weibull Plotting Method		Bayesian Method (Uniform Prior)	
		Characteristic Life: α	Shape Parameter: ß	Characteristic Life: α	Shape Parameter: ß
Bearings (roller type)	3557	132	4.102	129	5.18
Bearings (self-lubricating type)	87	NA	NA	NA	NA
Brake (springs and pads)	997	93.78	3.898	102	3.26
Bridge crane	150	90.39	4.748	97.2	4.39
Butterfly valves	126	88.16	2.833	90.49	3.91
Chain (link type)	514	63.8	5.115	63.09	8.71
Chain (roller type)	465	73.44	6.039	75.88	6.37
Check valves	737	68.28	5.698	71.73	5.05
Clutch (jaw)	56	104.8	2.154	99.29	3.26
Couplings (flexible)	1160	71.46	7.981	77.73	8.99
Couplings (rigid)	2147	140.3	4.228	141.98	4.67
Cylinders	1260	113.8	2.25	110.56	2.51
Flexible hydraulic hose	975	44.1	4.5	52	3.87
Gear reducer–parallel gears	1101	125	4.25	132.87	4.71
Jet/Howell bunger valve	24	45	0.76	55.02	1.33
Jib crane	64	124	1.8	128.49	2.07
Lifting stems	790	100.5	2.857	106.64	2.67
Manual control valves	798	96	2.68	88.84	3.27
Pipes (carbon steel)	1887	117.1	3.021	105	3.51
Pipe (galvanised)	52	NA	NA	NA	NA
Pipes (stainless steel)	211	90.62	1.517	94.42	2.11
Pressure relief valves	294	82.97	5.028	80.21	5.94
Pumps (fixed displacement)	422	75.42	4.245	80.16	3.93
Pumps (variable displacement)	50	51	10.2	54.57	10.15
Reservoirs	228	89.98	4.384	102.47	4.03
Right angle gear box	484	230.6	2.29	244.75	2.69
Fixed wheel/roller gates	90	NA	NA	NA	NA
Roller train for caterpillar gates	662	99.5	2.44	90.76	2.2
Caterpillar gates	180	69.66	18.34	106.99	5.76
Rotating shafts	1240	103.4	7.958	111.89	8.68
Screw actuator (electric)	359	70.8	4.049	83.98	3.35
Screw actuator (manual hand wheel)	213	71.43	4.098	85.57	3.33
Sector-bull gears	907	576.4	1.98	2119	2.19
Sheave gears	141	NA	NA	NA	NA
Slide gates	690	144.7	3.657	144.44	3.98
Sluice gates	532	134	2.584	123.42	2.9
Solenoid control valve	457	56.97	6.076	62.72	5.11
Stem nut	912	144.6	2.222	153.24	2.36
Spur-pinion gears	1139	NA	NA	NA	NA
Sprockets	436	NA	NA	NA	NA
Sump pumps	211	79.73	1.357	65.66	1.75
Trunnion pin and bearing	954	81.2	5.71	89.1	5.32
Wire rope (carbon steel)	1288	82.85	2.06	79.59	2.17

Component	Total Inventoried	Weibull Plotting Method		Bayesian Method (Uniform Prior)	
		Characteristic Life: α	Shape Parameter: ß	Characteristic Life: α	Shape Parameter: ß
Wire rope (drum)	515	NA	NA	NA	NA
Wire rope (flat)	369	56.81	3.261	59.97	4.33
Wire rope (multi-part sheaves)	376	105.4	4.843	112.82	4.75
Wire rope (stainless steel)	2049	77.35	2.349	74.92	3.04
Wire rope (sheaves)	1848	66.12	10.52	5496	0.62
Worm gears	373	71.02	7.242	92.18	7.69

Table A-4: Weibull Parameters for Electrical Components for USACE FRM Projects

Component	Total Inventoried	Weibull Plotting Method		Bayesian Method (Uniform Prior)	
		Characteristic Life: α	Shape Parameter: ß	Characteristic Life: α	Shape Parameter: ß
Brakes (DC rectifier)	902	74.95	5.171	80.86	5.18
Control cables (fiber optic)	24	NA	NA	NA	NA
Control cables (multi-conductor/twisted pair)	1342	66.88	5.94	72.63	4.36
Control Panel	1190	81.96	4.37	74	5.57
Circuit Breaker (fused disconnect)	2341	75.1	3.388	80.77	3.23
Electric Motors	1979	91.43	4.047	93.46	3.88
Encoders	190	56.62	4.063	54.35	4.32
Generators	402	48.84	3.454	49.97	3.21
Motor Control Centers (MCCs)	346	83.42	3.249	89.53	3.64
Motor Starter (full voltage)	1502	78.96	4.329	79.01	4.4
Motor Starter (reduced voltage)	156	59.6	10.35	483.02	0.57
Panelboard	431	82.39	4.958	83.45	4.95
Push-button Switches	4410	78.73	4.525	87.5	3.6
Power Cable (in conduit)	1203	70.03	6.345	73.07	5.08
Power Cable (buried)	129	85.25	2.914	84.89	3.12
Power Cable (in duct tray)	90	74.8	4.432	73.07	5.08
Power Cable (overhead)	46	105	1.72	112.5	1.84
PLCs	105	NA	NA	817.27	0.64
Rotating Cam Switches	255	51	19.4	91	7.76
Rotating Limit Switches	1717	77.65	6.414	82.07	6.87
SCADA	62	NA	NA	NA	NA
Selysn Indicator Motor	154	53.2	4.007	58.67	3.48
Switchboard	74	65.38	6.071	70.99	5.14
Switchgear	55	78.84	3.788	82.63	3.83
Transfer Switch (automatic)	130	57.33	3.54	57.57	3.63
Transfer switch (manual)	229	64.25	3.758	70.79	3.28
Transformer	360	70.48	3.298	71.14	3.26
Travelling Nut Limit Switch	43	NA	NA	NA	NA

3. **USACE Asset Management Operational Condition Assessments (2011).** Weibull data was developed for USACE Asset Management program in 2011 using Expert-Opinion Elicitation (EOE) of USACE Subject Matter Experts (SME) for various categories of components at navigation locks and dams. The EOE data was processed using Weibull probability plotting of the median response from the SME for each top category that contains ME components within each group. The top categories for mechanical and electrical equipment at navigation locks and dams are: Controls (6 and 7), Electrical (11 to 15), and Operating Equipment (23 to 28). Below are summary tables with Weibull information and component list for each category.

Table A-5: Weibull Parameters for Control Components from Asset Management National Weibull Curves

Asset Management Curve Title and Number	Period (years)	Weibull Parameters		Category	Component Name
		Beta	Alpha		
Control A - Curve #6	50	3.3	35.5	Electric Controls	Controllers
					Control Panels
					Control Relays
					Solenoids
					Control Cable
				Limit Switches and Positions Indicators	Stop Control Switches
					Safety Control Switches
					Position Indicators
					Position Gages/Displays
					Position Recorders
Control B – Curve #7	35	3	20	PLC Systems	HMI/PC Hardware
					PLC Software
					PLC Control Cable
					PLC Power Cable
					Panel Cabinets
					I/O Racks
					Displays
					Alarms
				SCADA	Communication Infrastructure
					Remote Terminal Units
					SCADA Controllers
					SCADA Power Cable
					SCADA Communication Cable
					SCADA By-pass Switches
					SCADA Interlocking Devices
				Misc. Solid-State Controls	Photo optic Controls

Table A-6: Weibull Parameters for Electrical Components from Asset Management National Weibull Curves

Asset Management Curve Title and Number	Period	Weibull Parameters		Category	Component Name
		Beta	Alpha		
Electrical A – Curve #11	60	4.7	47	Service Entrance Equipment	Service Transformers (Project Owned)
					Switchgears
					Motor Control Centers
					Switchboards
					Service Panels
					Voltage Regulators
					Power Factor Correction Capacitors
					Main Disconnects
					Substations (Project Owned)
					Main Breakers
					Protective Relays
				Main Power Feeders	Medium Voltage Feeder (>600V)
					Low Voltage Feeder (<600V)
				Power Distribution Systems	Panelboards (Operating Equipment)
					Panelboards (Lighting)
					Control Transformers
					Disconnects
					Breakers
					Fuses
				Conduits, Cable Trays and Supports	Conduits
					Cable Trays
					Cable Supports
Electrical B – Curve #12	60	2.9	45	Operating - Electric	Electric Motors
					Electric Brakes
					Motor Starters
					Speed Drives
					Contactors
					Control Relays
Electrical C – Curve #13	50	4.5	43	Lighting	Light Fixtures
					Power Cable
Electrical D – Curve #14	40	4.5	33	Emergency Power System	Generator Set
					Manual Transfer Switches
					Generator Fueling System
Electrical E – Curve #15	60	3.5	82	Grounding	Ground Mats
					Lightning Protection

Table A-7: Weibull Parameters for Operating Equipment from Asset Management National Weibull Curves

Asset Management Curve Title and Number	Period	Weibull Parameters		Category	Component Name
		Beta	Alpha		
Operating Equipment A – Curve #23	75	4.1	60	Mechanical	Gears
					Gear Boxes
					Linkages
					Clutches
					Sprockets
					Couplings
					Guides
					Sheaves
					Struts
					Torque Tubes
					Connecting Shafts
					Rotating Shafts
				Structural/Mechanical	Pintles
					Quoins
					Contact Blocks
Operating Equipment B – Curve #24	50	3.4	35	Mechanical	Brakes
					Bearings
					Bushings
					Pins
					Springs
Operating Equipment C – Curve #25	60	3.4	51	Hydraulic	Hyd. Cylinders
					Hyd. Motors
					Hyd. Pumps
					Hyd. Power Units
					Flow Control Valves
					Valves
					Hyd. Reservoirs
					Accumulators
				Water Driven Hydraulic	Control Gates/Wickets
					Turbine
					Pump
				Misc. Hydraulic Equipment	Filters
					Hyd. Piping
					Hyd. Hosing
Operating Equipment D – Curve #26	50	3.3	35.5	Water Pumps	Dewatering Pumps
					Raw Water Pumps
					Sump Pumps

Table A-8: Weibull Parameters for Operating Equipment from Asset Management National Weibull Curves cont.

Asset Management Curve Title and Number	Period (years)	Weibull Parameters		Category	Component Name
		Beta	Alpha		
Operating Equipment E – Curve #27	40	3.6	31	Compressed Air	Air Compressors
					Air Dryers
					Valves
					Regulators
					Gauges
				Steam System	Boilers
					Water Intakes
					Valves
					Gages
					Controls
Operating Equipment F – Curve #28	50	3.9	46	Miscellaneous Operating Equipment	Seals
					Fenders
					Cathodic Protection Systems
					Dogging Mechanisms
					Automatic Lubrication Systems

4. **Manual estimation of Weibull parameters.** Manual estimation of Weibull parameters should be used only when a component must appear in a fault tree, and it is not well described within the previous existing data sets. Before manually estimating Weibull parameters for a given component, consideration should be made to ensure that it is substantially different from components described in the previous data sets in either form or function. If the component is described in the previous data sets, but the CL does not reflect what is expected or has been documented at the project, consideration should be made to modify the existing data set using factors described in Attachment B of this guidance. This guidance will not go in depth as to the specifics of the methods available to estimate Weibull parameters but provides a description of some methods as well as the contexts in which they are best suited. This guidance does not provide an exhaustive list of all possible methods. All methods for manual estimation of Weibull parameters rely either on significant experience from experts or the presence of reliable documentation of failure and maintenance for that specific component in situ.

    a. Expert-Opinion Elicitation (EoE). EoE may be the best option for quantifying uncertainty and filling data gaps when maintenance data for the component does not or cannot exist. Expert elicitation is a formal and systematic process for obtaining and quantifying expert judgment to characterize the uncertainty about decision critical quantities, such as Weibull parameters. It does not create new knowledge; instead, it characterizes the state of knowledge about some issue or quantity that is uncertain. This process represents a considerable designated effort of highly qualified individuals and therefore has the potential to be a costly process in terms of both project budget and schedule. In addition to the experts required for elicitation, experienced, trained, and qualified facilitators should be leveraged to conduct the process to ensure reliability and accuracy of the results.

b. Median Rank Regression. Median Rank Regression (MRR) is a popular method for deriving Weibull parameters when sufficient failure and maintenance data is present to represent a large sample size for the component in situ. MRR fits a least squares regression line through the points of the linearized unreliability cumulative distribution function for a component. This method is readily available for use in reliability software packages such as Isograph's Reliability Workbench and Availability Workbench. This method can produce high levels of uncertainty when too little failure and maintenance data is available. This is the method used to derive the Weibull parameters of the overall system in the example shown in Attachment C of this guidance.

c. Maximum Likelihood Estimation. Maximum Likelihood estimation (MLE) has been argued to be a more statistically rigorous method for Weibull parameter estimation when compared to MRR. This method also requires a large sample size of failure and maintenance data. One of the primary benefits of this method is that methods for computation of confidence intervals are readily available. Computation of confidence intervals would allow for documentation of uncertainty of the estimate of the Weibull parameters. This method for parameter estimation is not as popular as MRR and is therefore less likely to be a built-in feature in reliability software packages.

d. Weibayes. The Weibayes method, as described by Abernethy (2006), is a Weibull analysis performed with an assumed beta Weibull parameter. This method is best used when a component does not have many failures documented, and the failure mode for the component is known with a high degree of certainty. Because beta is related to the failure mode for a component, beta can be estimated based on the known failure mode. When the sample size of failures for the component is small, and the beta is known with a high degree of certainty, the Weibayes method can be substantially more accurate than other estimation methods. The Weibayes method is also available for use in reliability software packages such as Isograph's Reliability Workbench and Availability Workbench.

ATTACHMENT B: Duty and Environmental/Load Factors

1. **Duty Cycles.**

Many mechanical and electrical components at navigation (NAV) and flood risk management (FRM) projects spend a considerable portion of time in periods of non-operation. While the component is not operating, it should be expected that its rate of failure will change. System failure characteristics should account for the duty cycle or period of operation for that component as well as changes in failure characteristics during periods of non-operation. For example, miter gate equipment is considered to have a negligible failure rate during periods of non-operation. Previous guidance accounted for this change in failure rate using a modifier, called a duty cycle factor. For example, the general equation for the reliability of a two-parameter Weibull distribution is given by:

$$R(t) = e^{-\left(\frac{t}{\alpha}\right)^{\beta}}$$

Where R(t) gives the cumulative distribution function of reliability over time, t represents time in years, α represents the scale parameter (CL) of the distribution, and ß represents the shape parameter of the distribution. This equation is modified by the duty cycle factor as shown:

$$R(t) = e^{-\left(\frac{td}{\alpha}\right)^{\beta}}$$

Where d is the duty cycle factor. The duty cycle factor would also modify the hazard rate for a given component. The general equation for the hazard rate of a two-parameter Weibull distribution is given by:

$$h(t) = \frac{\beta}{\alpha}\left(\frac{t}{\alpha}\right)^{\beta-1}$$

And when the duty cycle factor is applied, the equation becomes:

$$h(t) = \frac{\beta}{\alpha}\left(\frac{td}{\alpha}\right)^{\beta-1}$$

Duty cycle factor should also vary based on the expected failure mode for a component. The duty factor for lock mechanical equipment is directly related to the number of lockages or hard operations that occur at a facility, as the primary failure mode for that equipment is wear or fatigue. Conversely, a properly designed steel hydraulic pipe would not experience a significant change in failure rate during periods of non-operation, as its primary failure mode is corrosion. The hydraulic piping would therefore be expected to have a higher duty cycle factor than the miter gate equipment, even if they were operated at the same frequency. This is because the failure rate during non-operation is a higher portion of the failure rate during operation for the pipe than it is for the miter gate machinery.

Components also experience different loading conditions when not operating. For example, a wire rope that is attached to a crane may not actively be operating, but it may still be under load if attached to a lifting beam. Because of this, duty cycle factor should vary based on the loading condition of the system when not in operation, with higher duty cycle factors used for components that are normally under load when not in operation.

As part of the inputs to the failure models applied to the components of a fault tree or reliability block diagram, Availability Workbench allows the duty cycle factor to be represented using two different non-operating apportionment factors in the program that are defined below:

a. Non-operating failure apportionment % — The non-operating failure apportionment indicates how the failure rates of components associated with the failure model will be adjusted when they are not operational. An apportionment value of 50% indicates that the failure rate should be halved or mean time to failure doubled when it is non-operational.

b. Non-operating ageing apportionment % — The non-operating ageing apportionment indicates how the age of components associated with the failure model will be adjusted when they are not operational for the purposes of planned maintenance activity intervals. An apportionment value of 50% indicates that the component ages at only half the normal rate when it is non-operational. This factor will not have an impact on reliability estimates unless planned maintenance activities are added to the failure mode.

For these factors to be applied, the warm Standby option needs to be active for the component in the AWB fault tree model. Additionally, each component must have the "Use standby times to failure when operating" option selected so that the failure and ageing characteristics will be applied even when the component is operating. Table B-1 and Table B-2 give suggested non-operating apportionment factors for components based on expected failure mode and loading condition while not operating.

Table B-1: Suggested Non-Operating Apportionment Factors for a System Normally Under Load

Failure Mode	Non-operating Failure Apportionment Factor
Wear	15%
Fatigue	20%
Combination	25%
Corrosion	30%

Table B-2: Suggested Non-Operating Apportionment Factors for a System not Under Load when not Operating

Failure Mode	Non-operating Failure Apportionment Factor
Wear	15%
Fatigue	20%
Combination	25%
Corrosion	30%

2. **Environmental Conditions.**

Failure rates should also be modified to reflect differences in environmental and loading conditions. For example, two components that are otherwise identical may be expected to have different service lives if one of them is regularly exposed to corrosive agents or operates at a higher percentage of its nominal load rating. AWB allows for the user to account for these variations using the load factor.

Load factors may be assigned to individual events of the fault tree in AWB. The load factor is also variable during different operational phases, if operational phases are built into the model. The default value for load factor in AWB is 1. The load factor directly modifies the MTTF for a given event. For example, a load factor of 2 will increase the failure rate by 2 for the exponential distribution. This is equivalent to halving the MTTF. This is described by the general expression:

$$\text{MTTF} = \frac{\text{MTTF}_{\text{Normal}}}{\text{Load Factor}}$$

Environmental conditions must be defined for the ambient service conditions of the equipment. Environmental conditions to consider when creating a load factor for a component include, but are not limited to, factors such as:

- Operating temperature
- Whether it is exposed to the elements or is sheltered
- Whether it is exposed to corrosive agents such as salt water
- If it is in a high-vibration environment
- If it is operating at or above its nominal load rating

When applying a load factor to a component, it is important to keep in mind that the load factor will directly modify the MTTF for that component. Directly modifying the MTTF can have a substantial impact on the predicted reliability for that component and therefore load factors should only be applied after great consideration. It is important to apply load factors only when the actual environment or loading conditions differ from those assumed in the data source used to determine the component's failure characteristics. For example, assumptions for the CL's given in ERDC TR 13-4 (data source 1 from Attachment A of this guidance) are as follows:

- CL is the expected life until failure.
- Normal maintenance is done; there is no replacement.
- Operations are assumed to be "normal," i.e., there is no increase in future traffic.
- CL is expressed in years (no fractions).
- The general-purpose environment is "good."
- The typical lock and dam do not go underwater.
- All materials are properly selected and designed.

If ERDC TR 13-4 is used as the data source for a component's failure characteristics at a NAV project where routine maintenance has not been consistently performed, then the component's environment and loading conditions may differ from the assumptions underlying the reference data. A change in the load factor could therefore be justified to account for any differences. Any changes in the load factor should be documented and justified.

ATTACHMENT C: Application Example to Fault Tree and Reliability Block Diagrams in Availability Workbench

The following example shows the basic steps for obtaining system hazard function parameters using Fault Tree Analysis (FTA). This should be taken as an introductory example into FTA and is not comprehensive. For that, other resources or training should be consulted.

Step 1: Define the Limit State — The first step in this process is to define failure for the system, known as a "limit state". Limit states will vary from system to system for a myriad of reasons and thus the determination of a limit state should be coordinated with other members of the PDT to ensure the limit state chosen meets the needs for the analysis. For a further discussion of limit states, refer to Chapter 2 of EC 1110-2-6062.

For this example, the system to be analyzed is the operating machinery for a Tainter gate, which is commonly used on navigation dams. The limit state used for this example was "Tainter Gate Machinery Fault". This definition was further expounded upon by defining limit state as any state of the machinery in which the controls for the Tainter gate are operated and the gate does not function as commanded by the operator.

Once the limit state is identified, the first step can be completed by adding the Top Event into Isograph's Availability Workbench AvSim module version 5.0 (AWB). Since this example creates a fault tree rather than a block diagram, it is first necessary to change the AvSim module from the default reliability block diagram view to the fault tree view. Once the view is changed, the Top Event can be added. The Top Event represents realization of the defined limit state. Figure C-1 shows a screen capture of this step being performed in AWB.

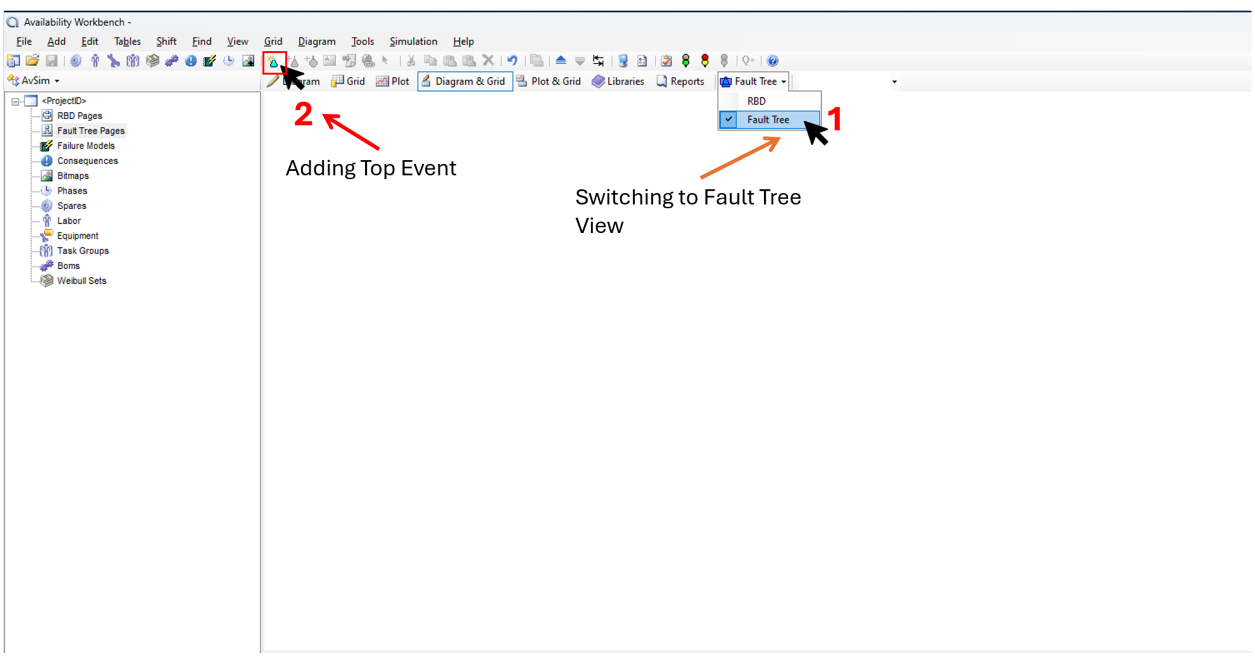


Figure C-1: Switching to Fault Tree View and Adding a Top Event

Once the Top Event is added, it can be labelled by double clicking on the icon and adding the label to the "Description" box.

Step 2: Identify the Critical Components or Events — The next step in the process is to identify the relevant components whose failure would constitute a realization of the defined limit state. For many mechanical systems with similarly defined limit states to this example, it is often useful to follow the path of energy from the controller for the system and work towards its point of application to identify the relevant components. In this case, the energy path starts at the controls in the form of a control signal and ends at the Tainter gate by it being moved in the desired manner. Figure C-2 shows a drawing for this system and identifies the key components.

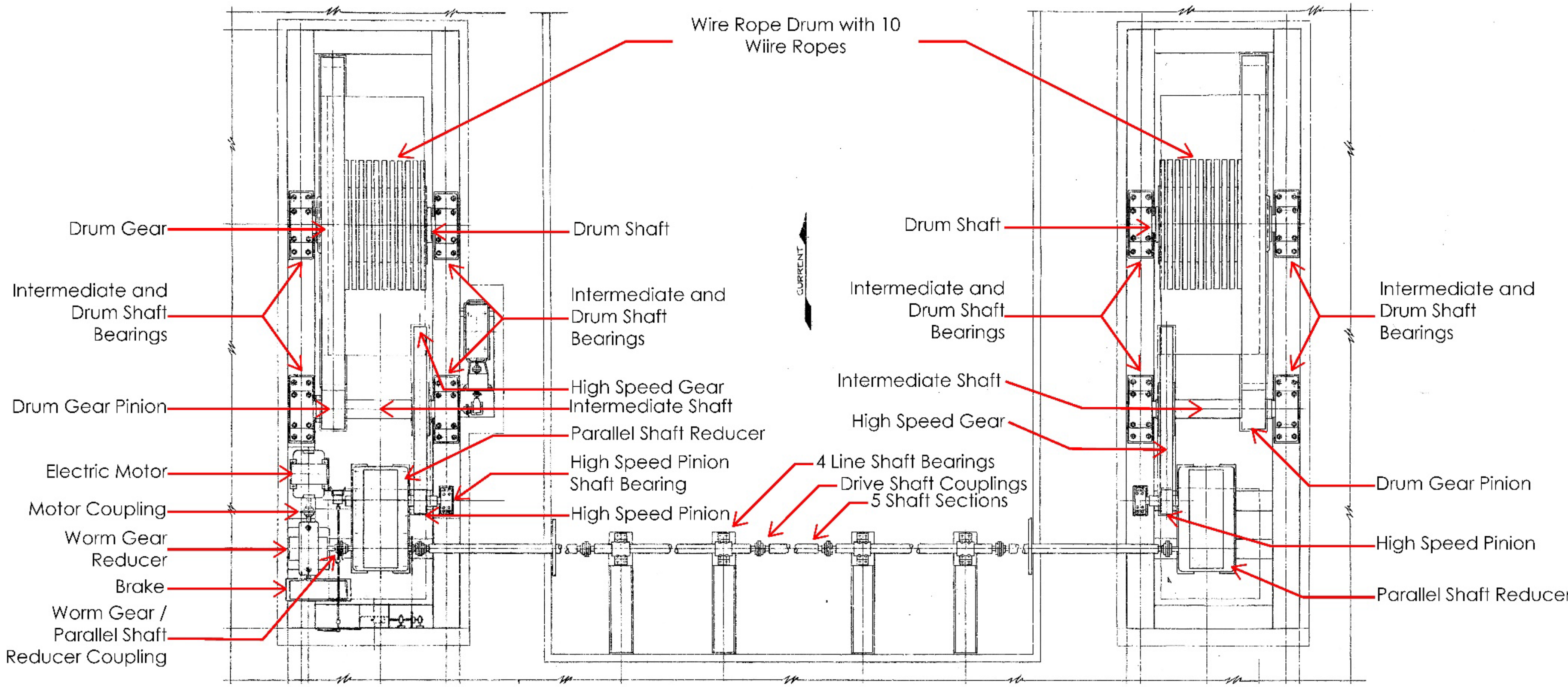


Figure C-2: Drawing of Tainter Gate Operating Machinery with Labeled Relevant Components

First, note that all relevant components may not appear on the drawing. For example, the physical controls for the machinery are not present on the drawing. A failure of the controls would result in the control signal never reaching the machinery and would thus constitute a realization of the defined limit state, as there are no arrangements made for manual backup operation.

Additionally, when determining relevant components, consider a complete cycle of operation of the system and continuously refer back to the limit state. For example, the brake system is not necessary to raise or lower the gates, but the brakes are often used as a mechanism to hold the gates at a desired height above the sill. If the brake rectifier fails to actuate the brake, or if the brake itself fails to hold the machinery in place, the gate could fall and potentially cause damage. Because this failure would constitute realization of the limit state, the brake and its rectifier become relevant components in the fault tree.

Also note that just because a component appears in the drawings, failure of that part would not necessarily cause a realization of the limit state. For example, this machinery is equipped with a limit switch. The limit switch is only present as a safety mechanism to prevent raising the gate to a height that would engage the switch, and operational protocols are in place that prohibit raising the gate to that height. Therefore, a failure of the limit switch would not constitute a realization of the limit state because the limit switch is not relevant to operations of the gate within allowed operational protocols, and operation of the gate outside of those protocols would either indicate a failure of the machinery that is already accounted for, or an error of operation which is not accounted for in FTA under this methodology.

Finally, note that almost all components are comprised of assemblies themselves. For example, the parallel shaft reducers are each comprised of multiple internal gears and shafts. Determinations as to the depth that fault trees should go to should be made based on the resultant complexity of the fault tree, desired level of effort, availability of failure data, the defined limit state, the overall size of the system to be analyzed, and many other factors. In general, the best practice is to limit the complexity of the fault tree, when possible, given available failure data.

Step 3: Construct the Fault Tree — Now that the key components have been identified, the next step is the construction of the fault tree in AWB. The physical structure of the system to be analyzed should inform the structure of the fault tree. Fault trees are composed of two basic structures: logical gates (gates) and events. In this application of FTA, "events" normally represent parts within the system, such as shafts, gears, and bearings. There should be one event created for each part in the system whose failure could cause the limit state to be realized. Gates perform logical operations and help to organize the fault tree. In these applications, they will specify "or", "and", or "vote" logical operations. For an "and" gate to become true, all components under the gate must be true. For an "or" gate to be true, any one of the components under the gate must be true. Finally, in order for a "vote" gate to be true, a number of components, as specified in the gate must be true for the gate to be true. As an example, a "vote 2" gate will be true if exactly two of the components under the gate are true at the same time. These different logical operations are used to reflect the structure of the system to be analyzed. For example, "and" gates are frequently used to reflect redundancies or backups designed in a system, such as parallel pumps. Figure C-3 shows the buttons to add these structures into the fault tree.

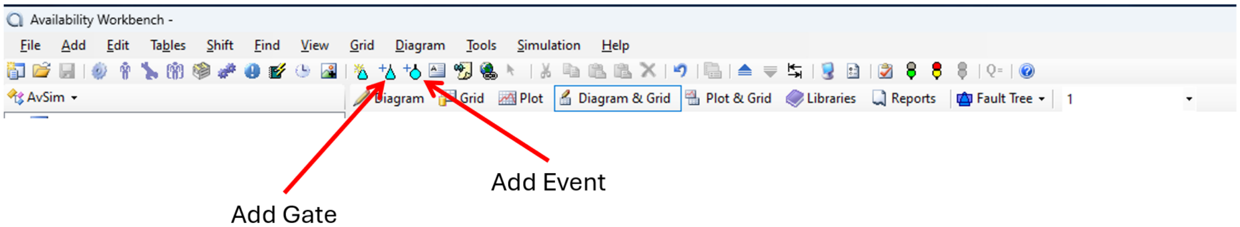


Figure C-3: Location of Buttons to Add Events and Gates into Fault Tree

Events are added by clicking the "Add Event" button and then clicking the gate that the event would belong to. Gates are added in the same manner. This process of adding gates and events continues until all the key components and events have been added to the fault tree. Figure C-4 through Figure C-12 show the structure of the fault tree that was used to analyze the hoist machinery shown in Figure C-2.

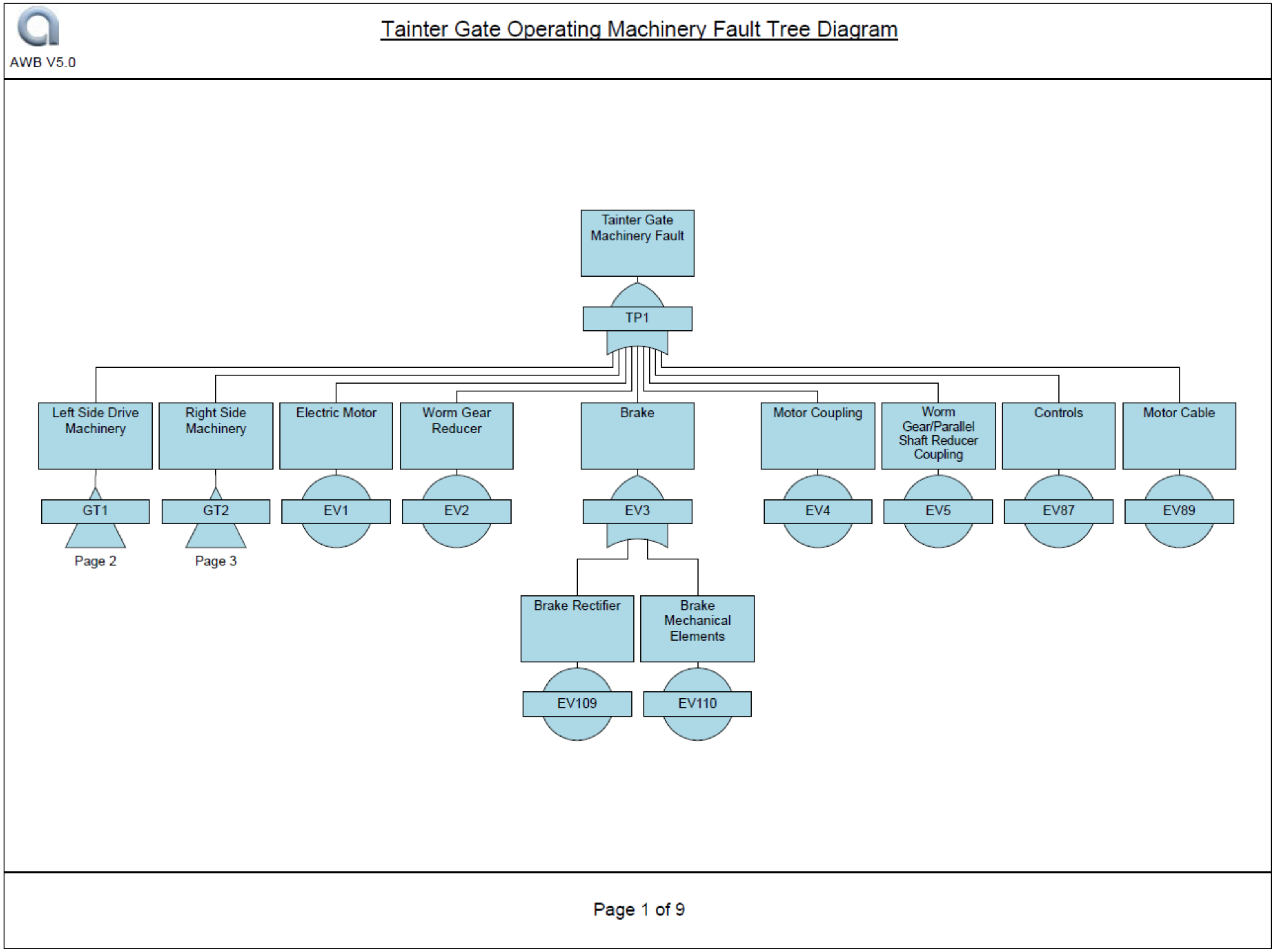


Figure C-4: Page 1 of Tainter Gate Hoist Machinery Fault Tree — Central Drive Components

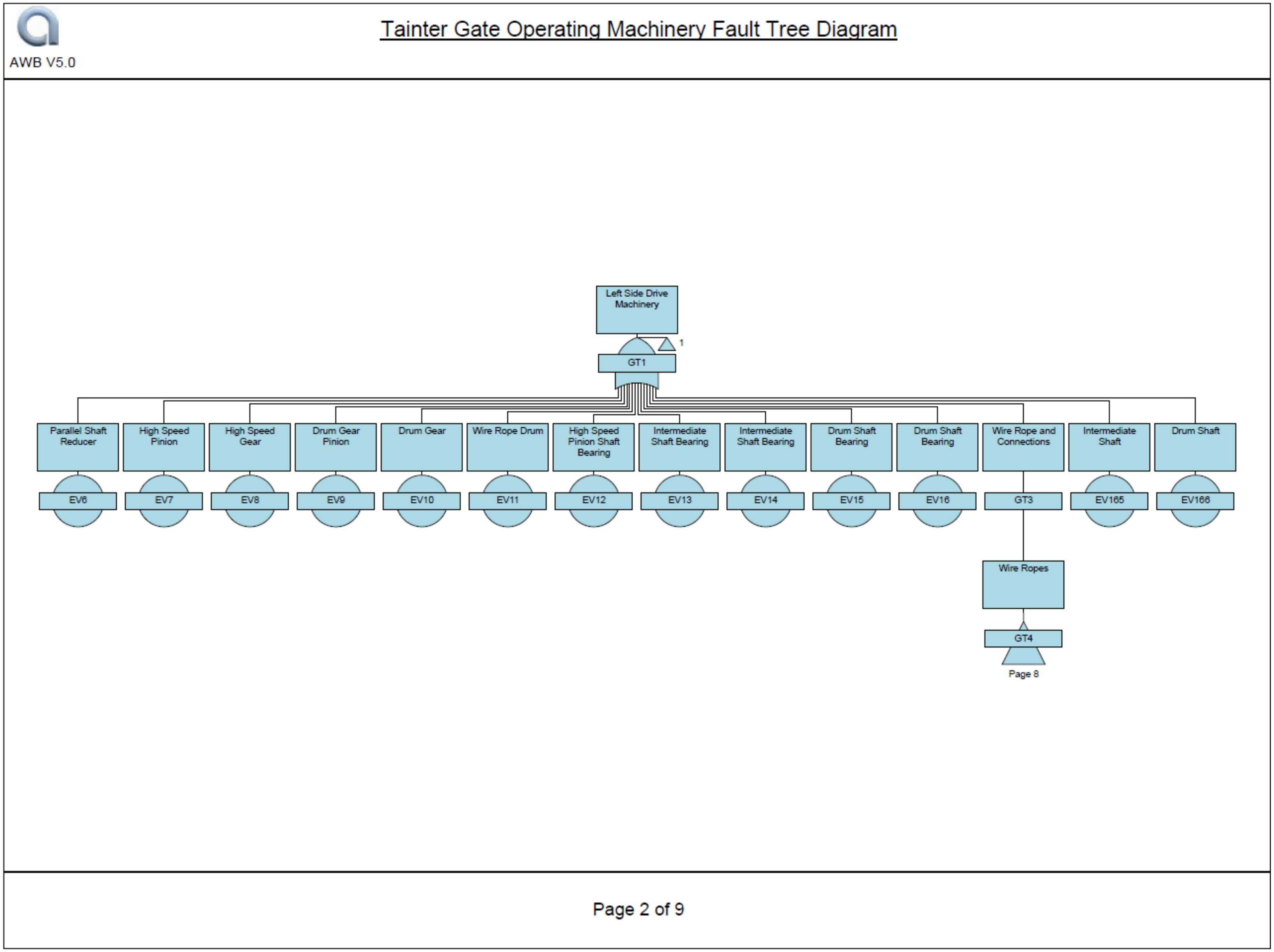


Figure C-5: Page 2 of Tainter Gate Hoist Machinery Fault Tree — Left Side Drive Machinery

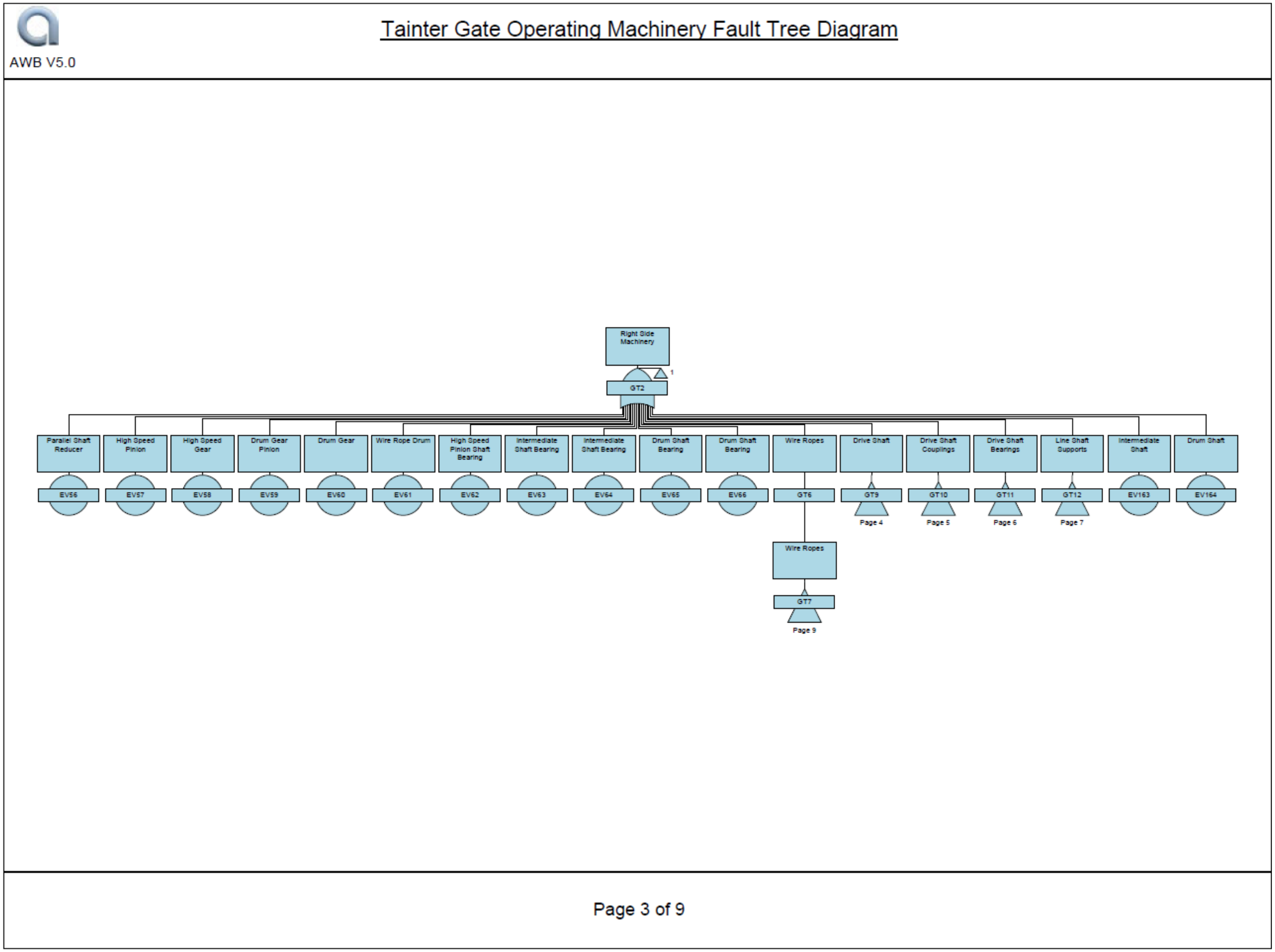


Figure C-6: Page 3 of Tainter Gate Hoist Machinery Fault Tree — Right Side Machinery and Drive Connection Components

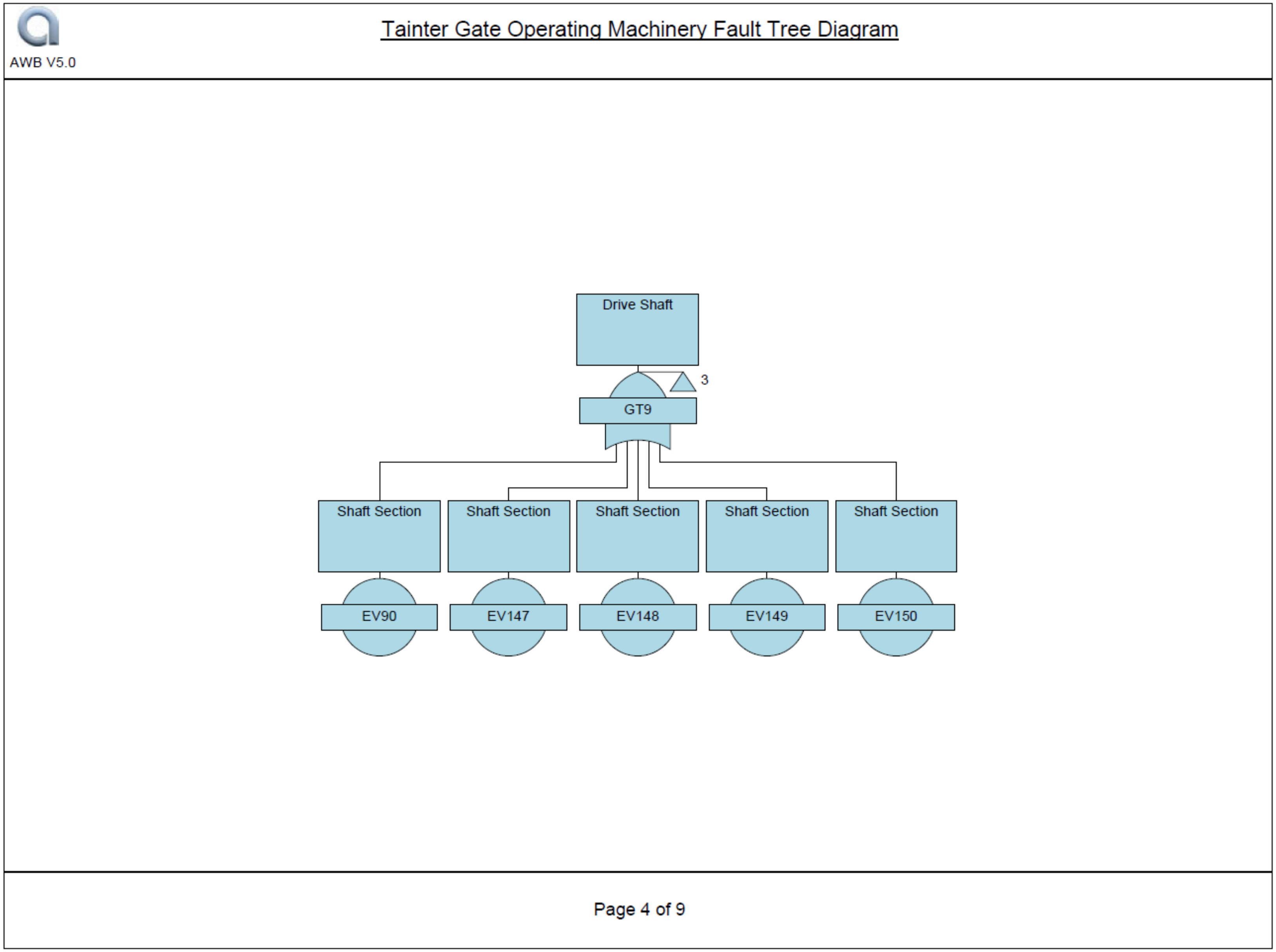


Figure C-7: Page 4 of Tainter Gate Hoist Machinery Fault Tree — Drive Shaft Sections

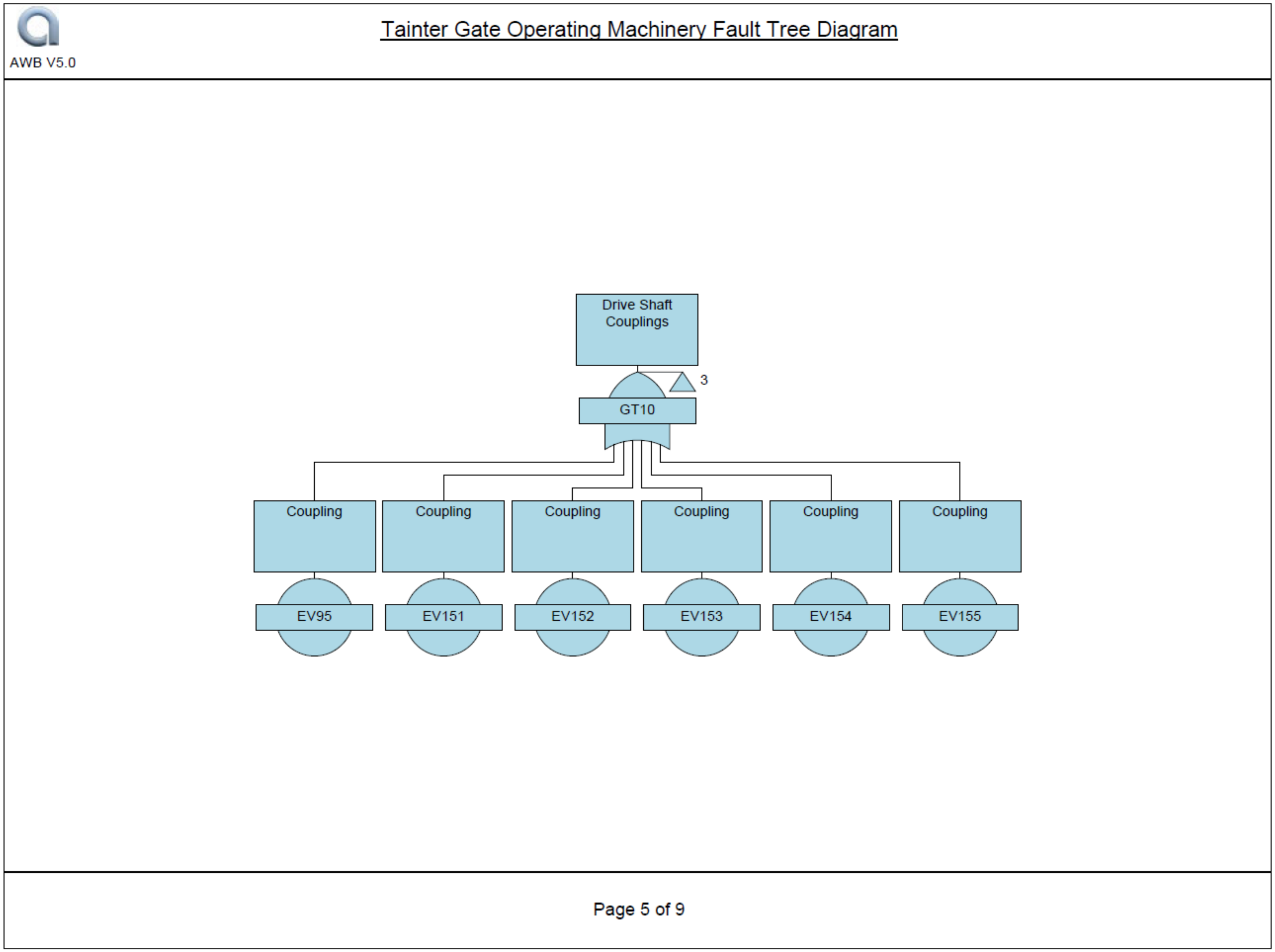


Figure C-8: Page 5 of Tainter Gate Hoist Machinery Fault Tree — Drive Shaft Couplings

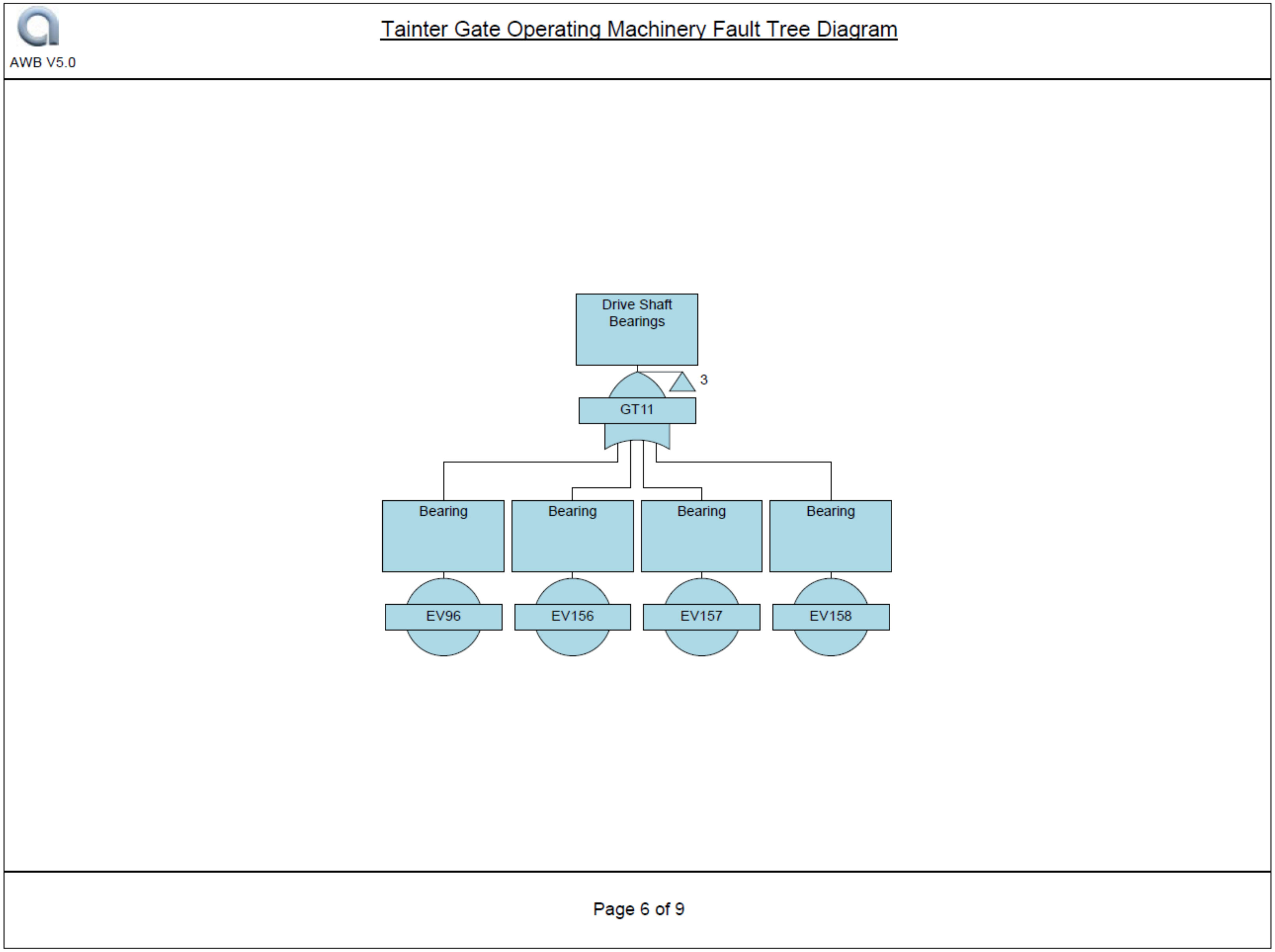
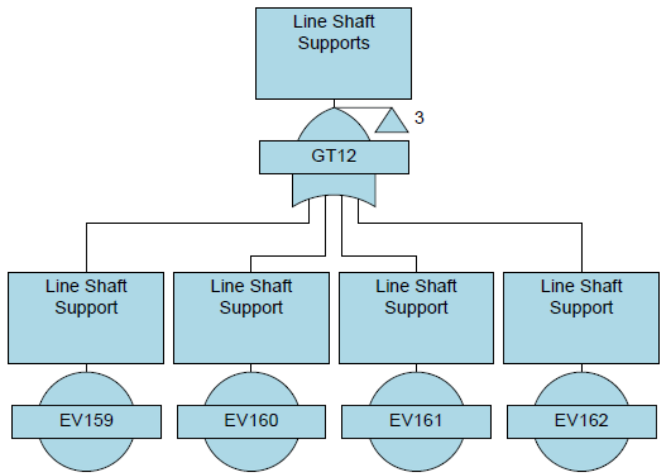


Figure C-9: Page 6 of Tainter Gate Hoist Machinery Fault Tree — Drive Shaft Bearings

AWB V5.0

Tainter Gate Operating Machinery Fault Tree Diagram



Page 7 of 9

Figure C-10: Page 7 of Tainter Gate Hoist Machinery Fault Tree — Line Shaft Supports

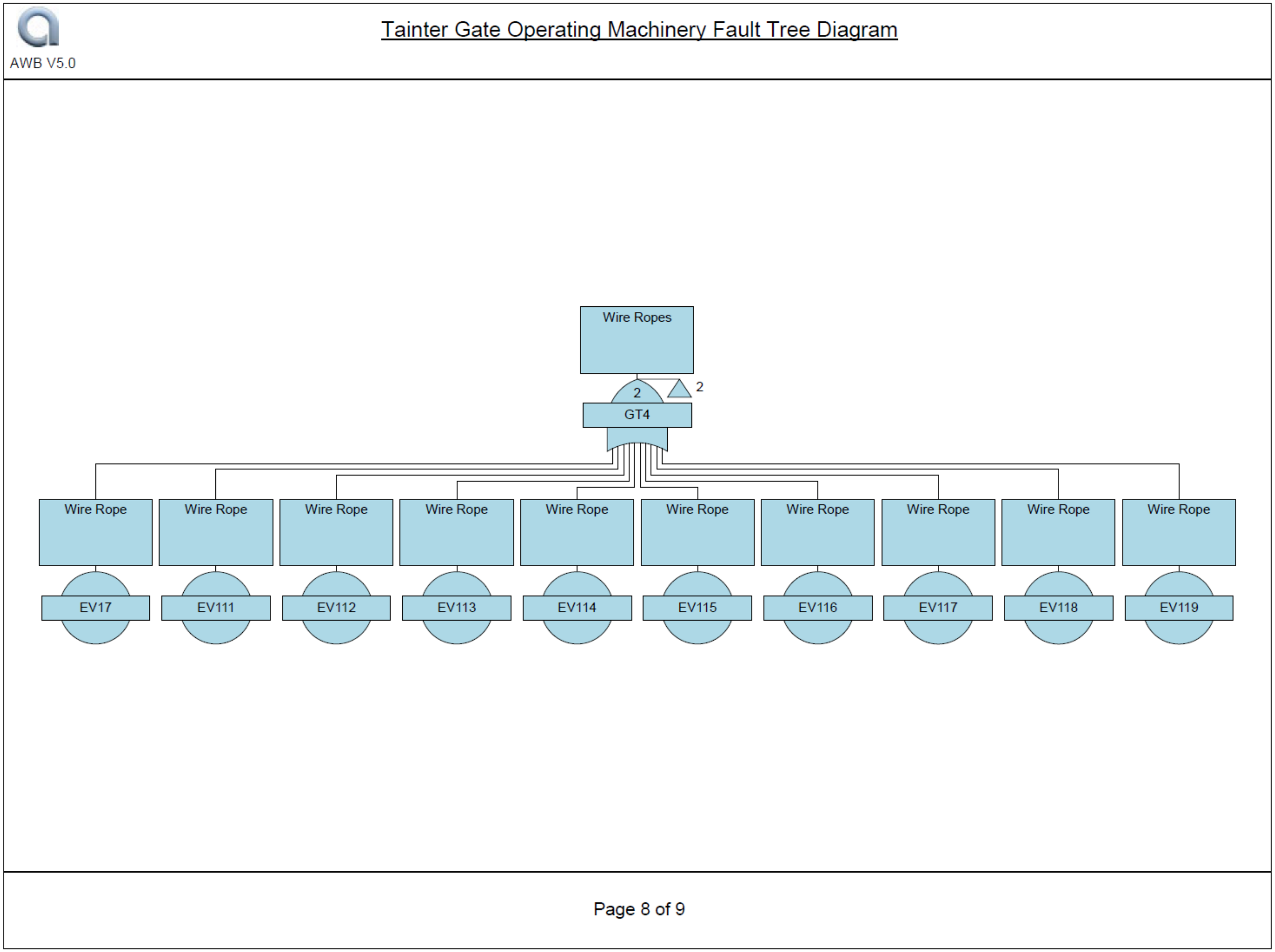


Figure C-11: Page 8 of Tainter Gate Hoist Machinery Fault Tree — Left Side Wire Ropes

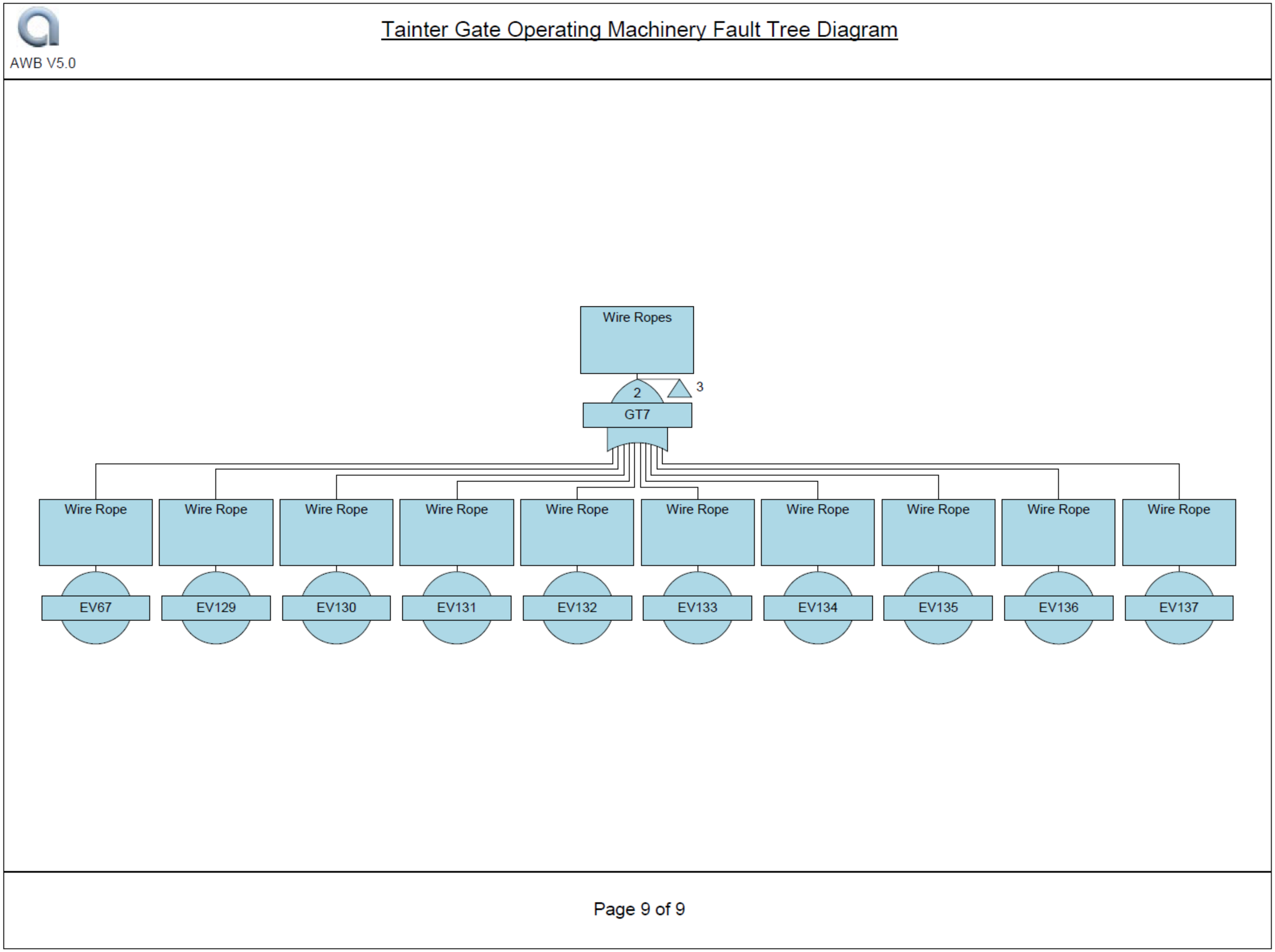


Figure C-12: Page 9 of Tainter Gate Hoist Machinery Fault Tree — Right Side Wire Ropes

As can be observed in Figure C-4, logical gates can also assist in organizing the fault tree for better understanding and visualization. The shared drive components of the hoist machinery are found on the first page directly under the Top Event, with the drive machinery that is located on either side of the system organized under their own logic gates. The fault tree progresses from there, organizing the separable systems into their own gates for ease of understanding and organization.

Note that gates GT4 and GT7, which contain the events for each of the wire ropes, are "vote" gates, not "or" gates, as the rest of the gates in the model are. This is denoted visually within the fault tree with the "vote number" for the gate being displayed near the "point" of the gate symbol. This was added as a vote gate, as it was determined that two or more wire ropes would have to fail simultaneously in order to constitute a failure of that system.

It should be noted that there are multiple valid ways to structure the fault tree for this system, depending on user preference. For example, the gate in the middle of Figure C-4, "EV3", which contains the electrical and mechanical parts of the brake could be eliminated, and these parts be put directly under the top event.

Step 4: Add Failure and Maintenance Data — After the structure of the fault tree is complete, failure distributions and maintenance data for each component must be added. Failure and maintenance data should be added using the guidelines and data sets from the Attachments A and B of this guidance. It is important to note that the units for failure, maintenance, and simulation duration must all be consistent. The most common unit of time used for this analysis is years. Values less than a year should represent the fraction of a year that the duration is, expressed in decimal form. As an example, one day would be equal to 1/365 or 0.00274, and one month would be 1/12 or 0.08333. Figure C-13 shows the steps to create a new failure model in AWB.

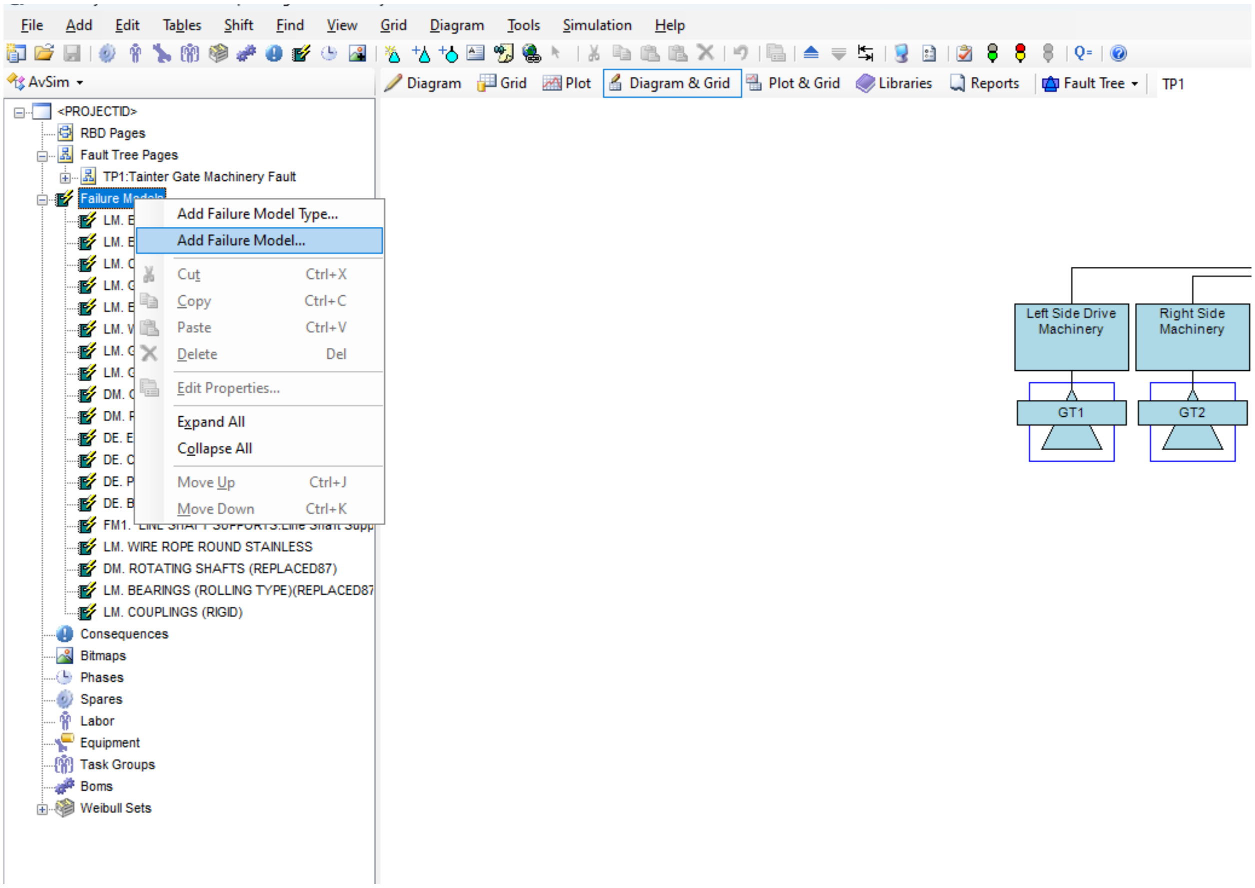


Figure C-13: Steps to Create a New Failure Model

With the “Failure Model Properties” interface open, first name the failure model. The suggested naming convention is to name the failure model after the component for which the failure model belongs, referencing what the equivalent component is called in the data sources, and including any relevant replacement information. For example, the suggested ID for the failure model for the drive shafts would be “Shafts Replaced 87”, or something similar. This component was seen as equivalent to “Shafts”, as recorded in ERDC TR 13-4, which is the source of the characteristic life for this component. 87 refers to the year in which the component was replaced, 1987, which was 23 years after the construction of the project. Although not required to ensure a model that is technically sound, it is recommended as this step will make the process more transparent for reviewers and others.

The location parameters, gamma (γ), is the third parameter used for Weibull distributions to represent failure characteristics for components in these fault trees. This parameter is used to reflect maintenance efforts through the years on different components of the system. It is calculated by subtracting the year in which the component was replaced or rehabbed from the beginning operating year of the system to which the component is a part of. This replacement or rehabilitation must have rendered the component to “like new” condition. As an example, a component that was replaced in 2010 that is part of a system that began operation in 1998 would have a location parameter of 12.

After the failure model is named, the failure data can be entered by navigating to the "Failure" tab of the "Failure Model Properties" interface. Instructions from Attachments A and B of this guidance should be used to assign appropriate failure data. "Eta-1" in the interface is equivalent to the appropriate characteristic life of the component. "Beta-1" in the interface is equivalent to the appropriate shape parameter of the component. "Gamma-1" in the interface is equivalent to the appropriate location parameter of the component. Figure C-14 shows the failure distribution inputs that were used to represent "Shafts Replaced 87".

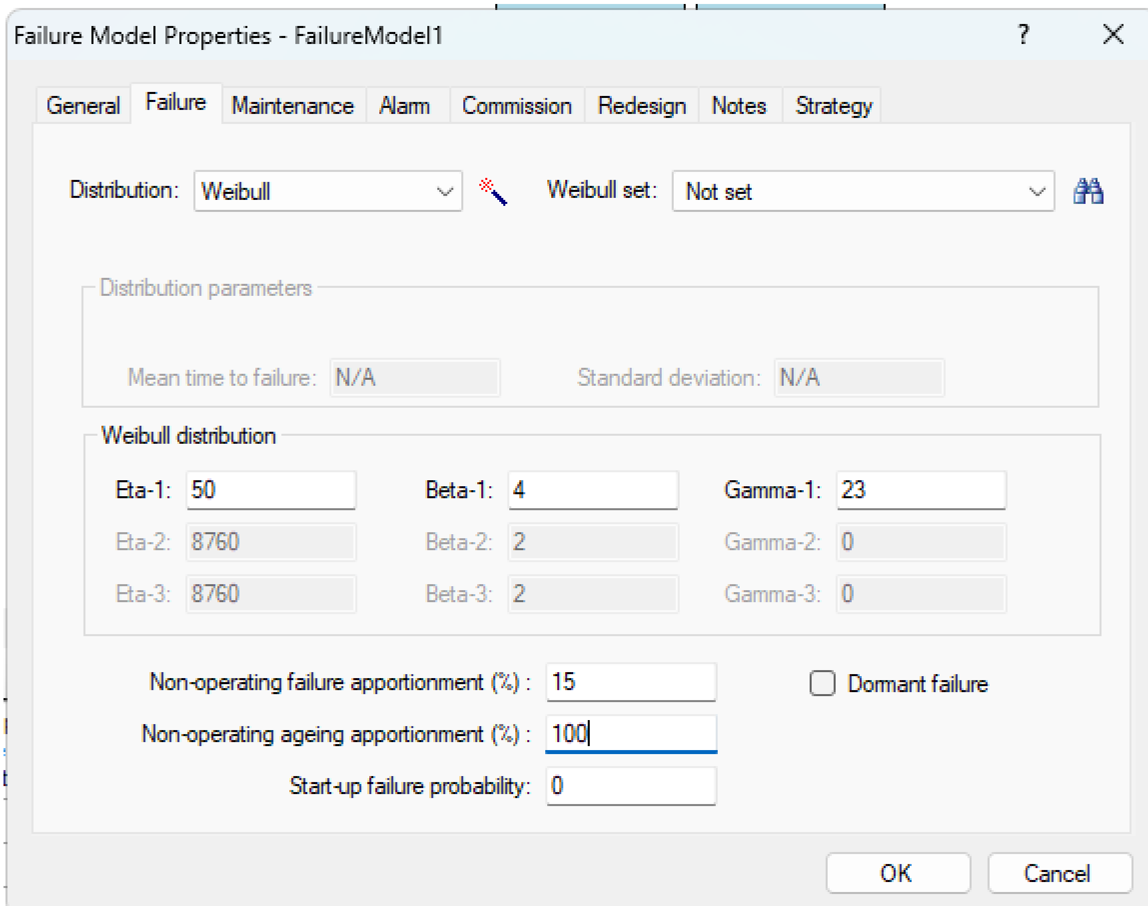


Figure C-14: Example Failure Model Inputs for Rotating Shaft Replaced 23 Years Following Project Construction

After failure distribution information is entered, corrective maintenance information must also be entered by navigating to the "Maintenance" tab of the "Failure Model Properties" interface. Maintenance task durations begin at the instant the part fails and do not conclude until the part is restored to operation. This includes the time to bid, award, and execute a contract if necessary. Figure C-15 shows the steps to enter the minimum maintenance information required.

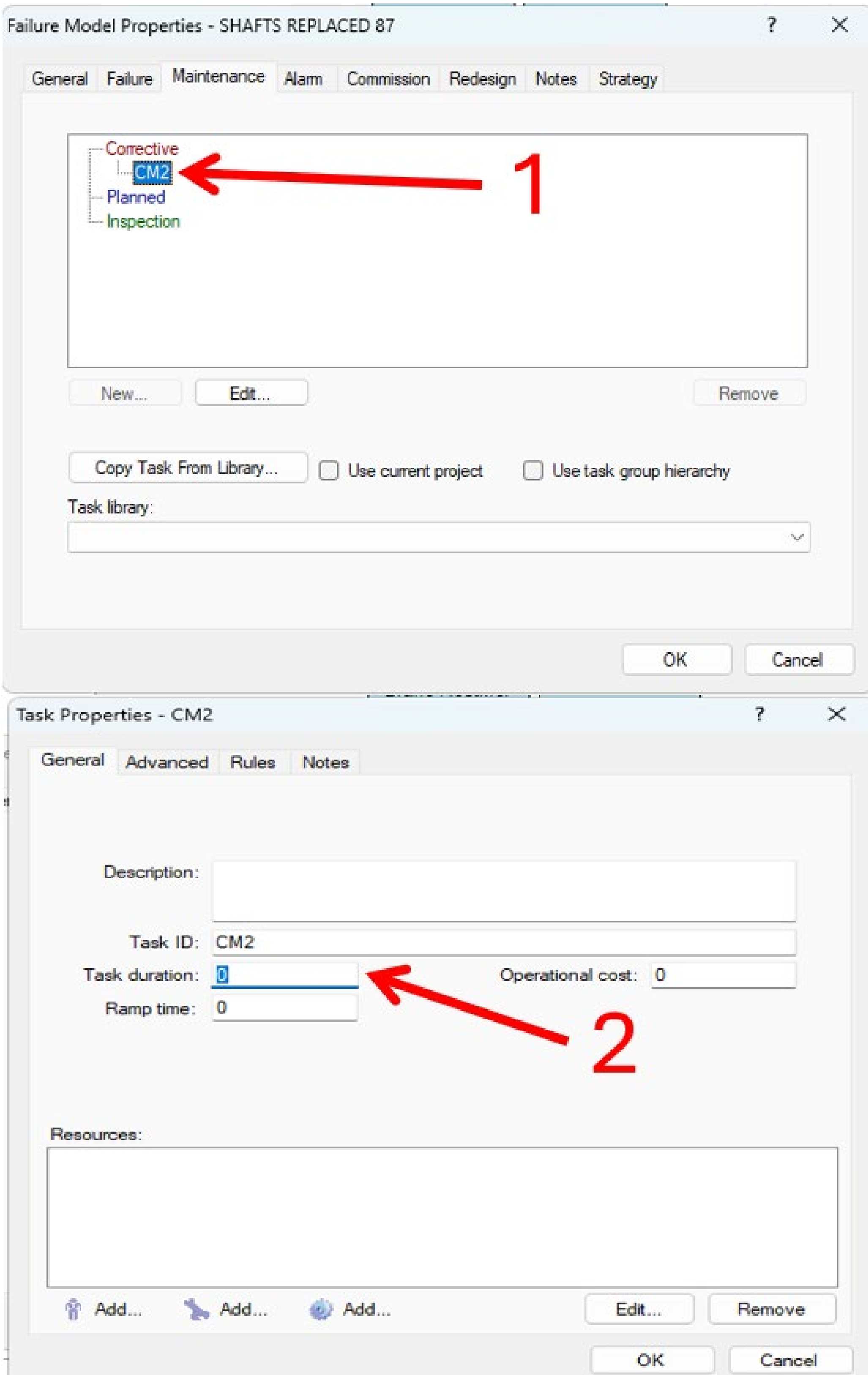


Figure C-15: Steps to Enter Minimum Maintenance Information for Components

AWB allows the user to enter substantially more information on maintenance for each component than is required to attain the reliability data used to generate a hazard curve. The information presented within this example represents the minimum amount of maintenance information to generate a hazard curve. Maintenance task durations will vary based on many different factors, and each should be carefully considered to determine the average maintenance duration. The maintenance duration entered should be reflective of the average duration of a repair following a realization of the most common failure mode for that component that would cause a realization of the limit state. In this way, the maintenance duration should reflect more than the labor hours necessary at the project site to make the repair. It should reflect the duration of all actions needed to complete the repair which could include contract actions and budget submittals. For this reason, two of the most important considerations when generating the estimated duration are: the criticality of the part to achieving the project's overall mission and the availability of repair funding.

The priority of every project is meeting its mission. Repair funding and time are finite resources and must be prioritized in a manner such that the machinery that is most critical to the project's success is repaired first. The electric motor in this example is part of the dam gate operating machinery for a lock and dam which has twelve dam gate bays. In the event of failure of this electric motor, there would still be eleven operable dam gates capable of maintaining navigational pool, which is the primary mission this system serves for the overall project. While this motor plays an important role in the system, the built-in redundancy of multiple dam gates means its temporary unavailability of one dam gate bay would not immediately jeopardize mission success. Therefore, although the motor remains a valuable component, its repair may be scheduled after more critical, non-redundant components and cause its total maintenance duration to be longer than might be initially expected.

When considering the availability of repair funding, both the estimated cost of the most likely repair and the available maintenance funding at the project should be considered. If repairs are costly enough, a budget package will need to be submitted which would increase the total expected maintenance duration to encompass the time during which funding is being secured. If project funding for maintenance is already limited, even less costly repairs may need time allocated to secure funding. Overall, engineering judgement and PDT collaboration should be used to generate the most reasonable maintenance duration for each part in the fault tree.

Once all relevant failure models and maintenance durations are created, they can be added to the appropriate events in the fault tree. Figure C-16 shows the interface for assigning a failure model to an event in AWB. This is done by double clicking the event that represents the desired part, clicking the drop-down menu, and selecting the appropriate failure model. It is because of this interface that the naming convention for each failure model is suggested, as a properly organized naming convention will make for easy identification of the appropriate failure model for the event.

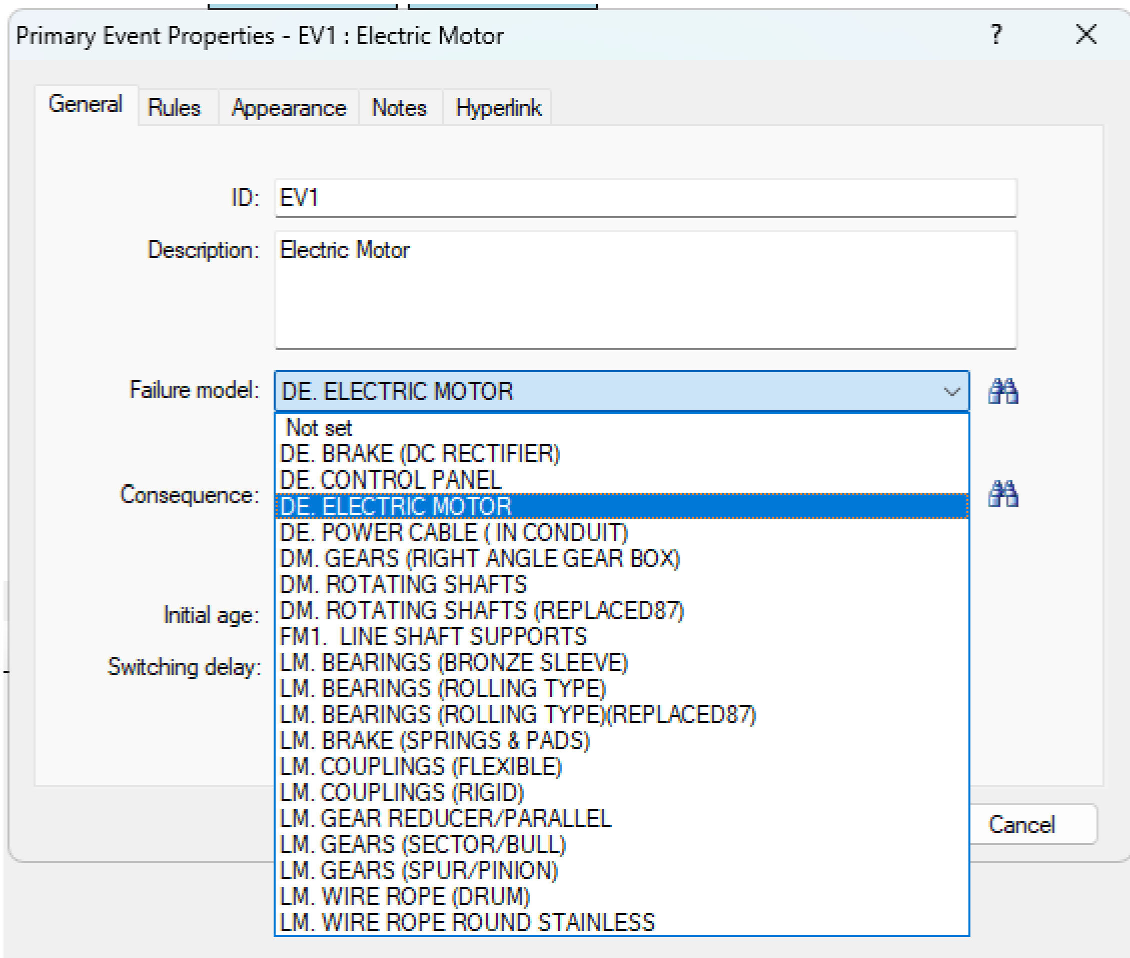


Figure C-16: Selecting a Failure Model for a Component

After the event has a failure model assigned, other parameters must also be updated. This is done for each event by navigating to the “Rules” tab of the “Primary Event Properties” interface. Figure C-17 outlines the necessary changes to this tab for each event in the fault tree.

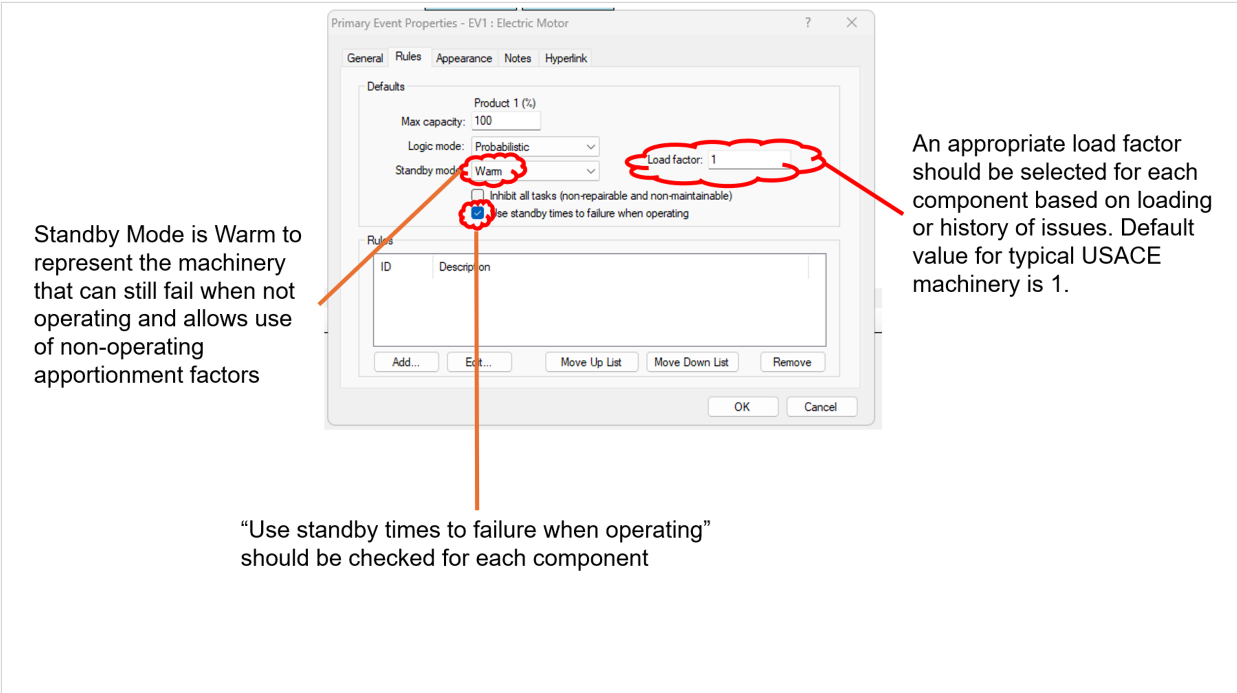


Figure C-17: Changes to the "Rules" Tab for Each Event in the Fault Tree

Once all the data is entered for each component, there are a few checks that can be done to ensure everything was entered correctly. First, there is a tool in the toolbar that will verify each component has a failure model assigned to it, shown in Figure C-18.

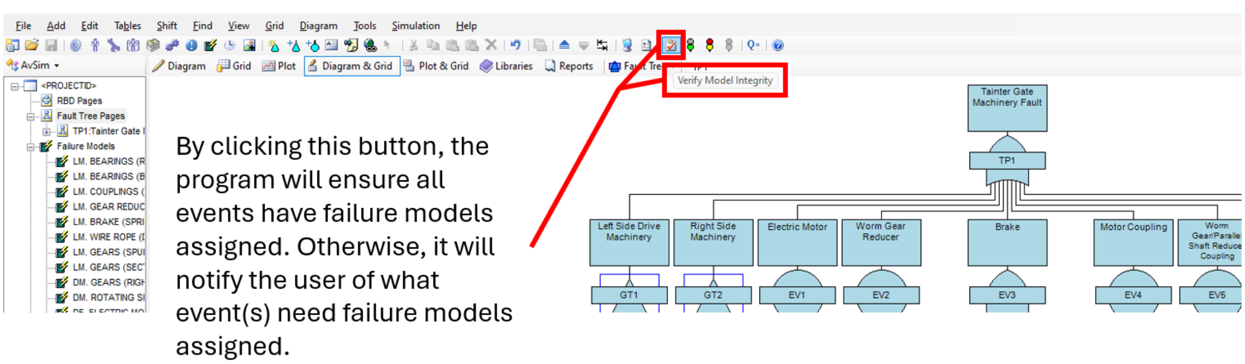


Figure C-18: Using "Verify Model Integrity" Tool

An additional check can be performed by viewing the grid for the primary events and ensuring that all components have the correct failure model assigned and that the modifications to the “Rules” tab for each have been properly made, as shown in Figure C-19. This interface can also be used to quickly modify assigned parameters if errors are discovered. Similar checks should also be performed for the created Failure Models by using the same interface and clicking on the “Failure Models” option from the drop-down menu.

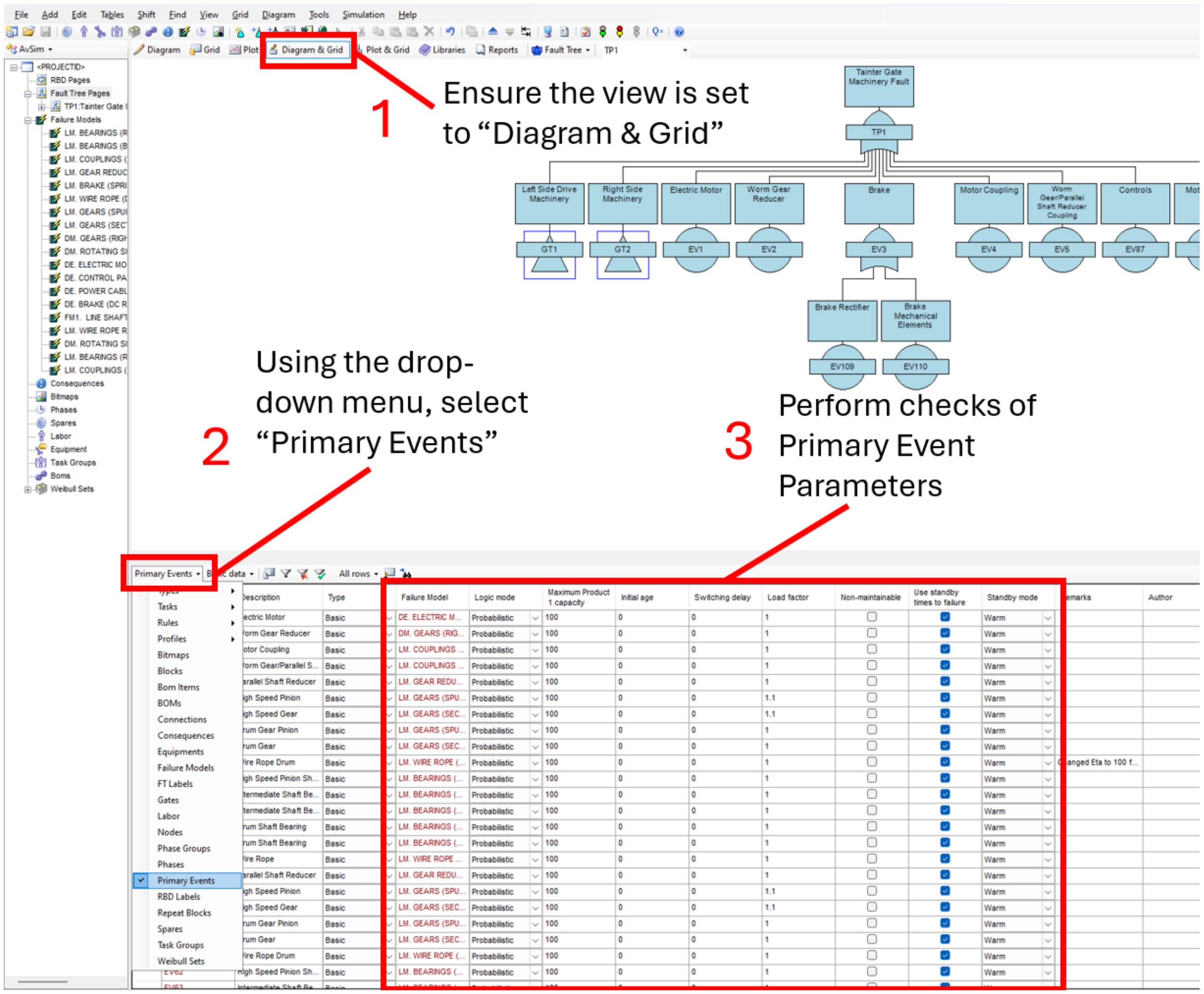


Figure C-19: Checking Primary Event Parameters

Step 5: Set the Modeling Parameters — With the structure of the fault tree in place and the failure and maintenance data set for each event, the modeling parameters must be set. The steps to accomplish these modifications are outlined in Figure C-20 and Figure C-21.

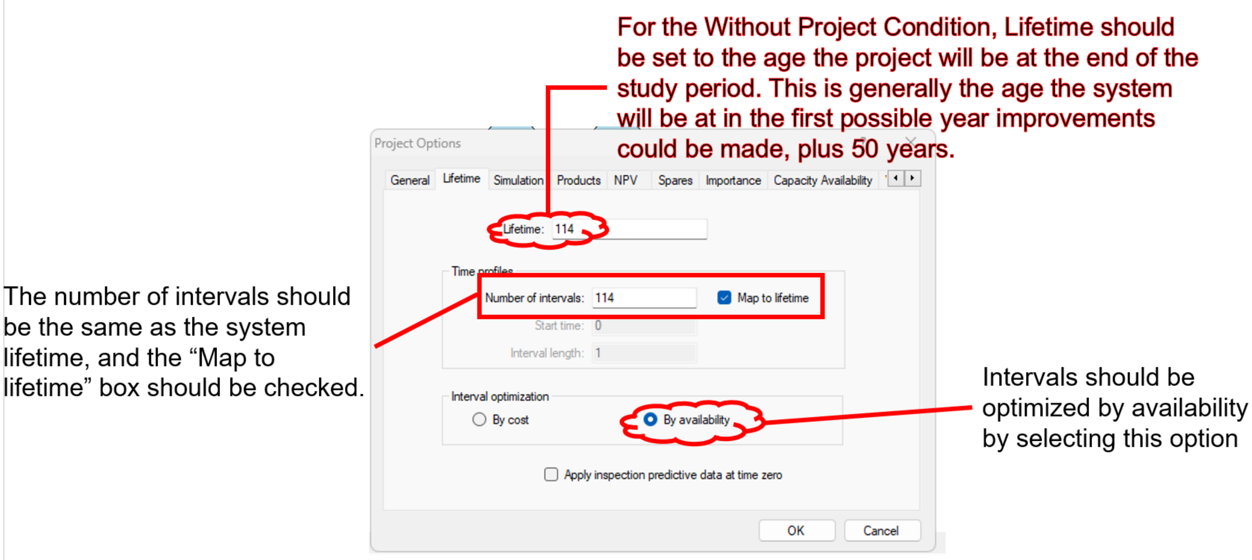


Figure C-20: Setting System Lifetime, Intervals, and Interval Optimization

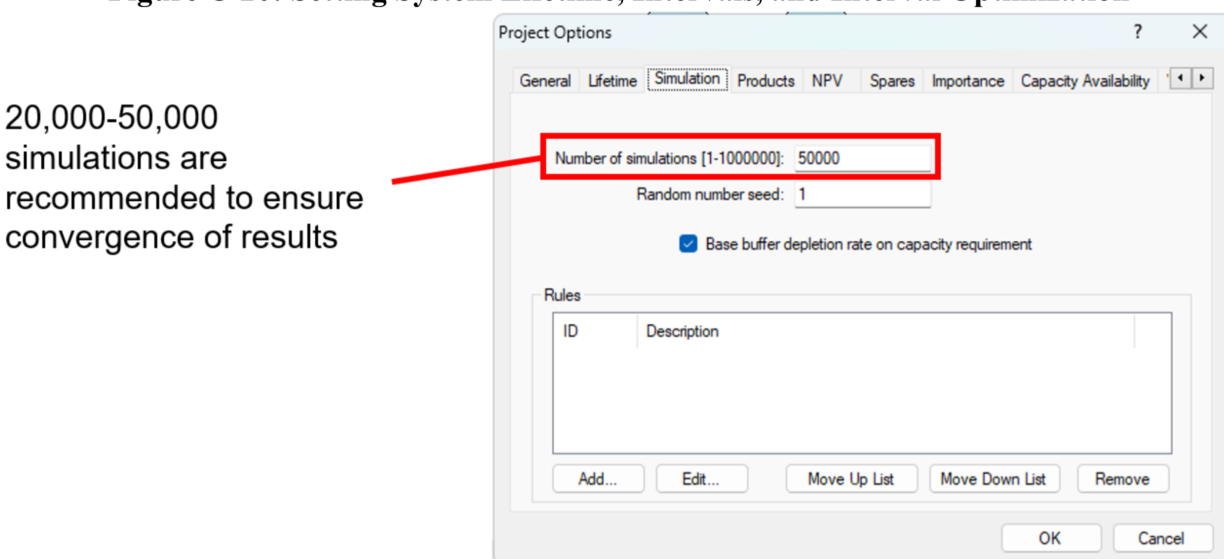


Figure C-21: Ensuring an Appropriate Number of Simulations

Step 6: Run the Simulation and Print Results— Once the system parameters are set, the simulation should be run, and the results should be outputted from the program. There are two main ways to run the simulation. The first and most simple is to simply click the “Start Simulation” button, as shown in Figure C-22.

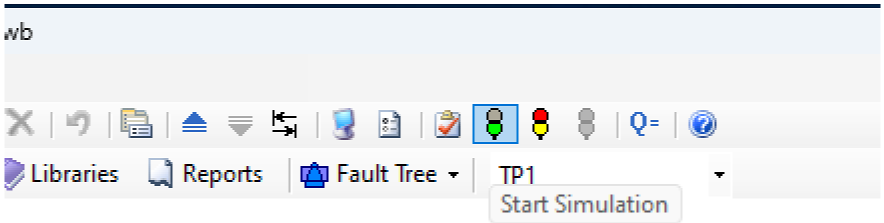


Figure C-22: "Start Simulation" Button

It can also sometimes be useful to "watch" simulation runs, or have the program record the precise results of each simulation. Each of these can be accomplished by clicking the appropriate option under the "Simulation" tab, as shown in Figure C-23.

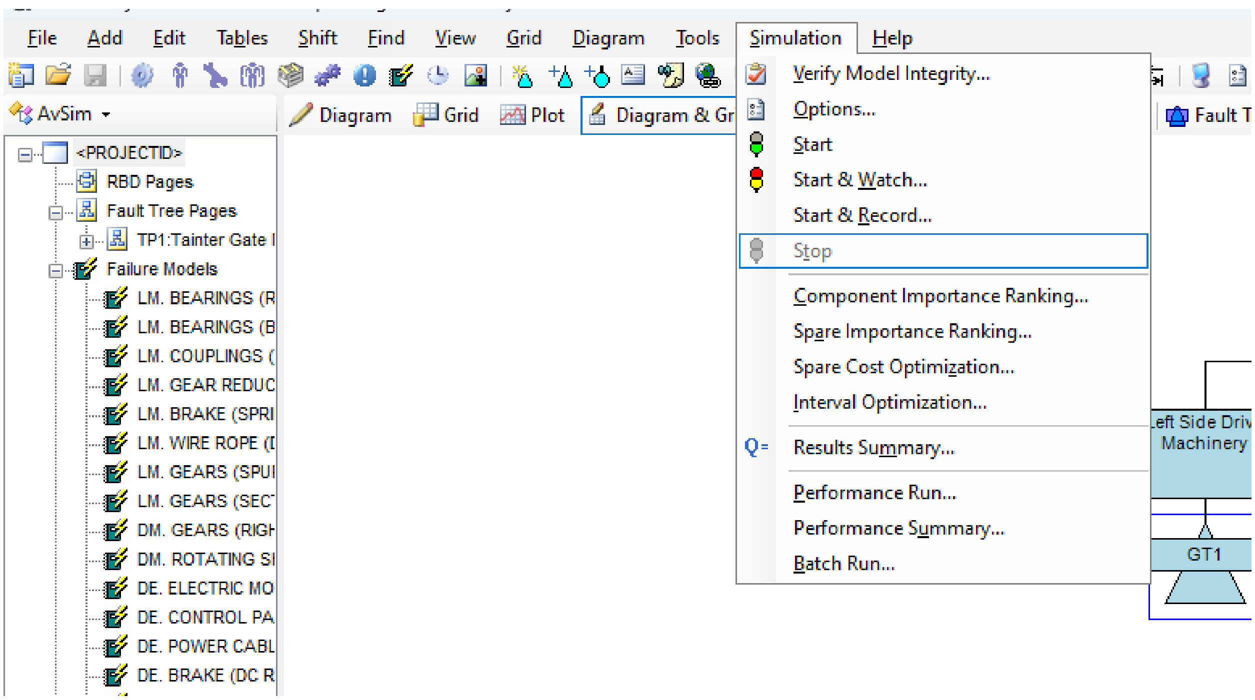


Figure C-23: Using the "Simulation" Tab to Access "Start & Watch" and "Start & Record" Functions

The software will then perform the Monte Carlo simulation based on the system parameters set. Once the simulation is complete, the results must be exported for further analysis, as shown in Figure C-24 through Figure C-28.

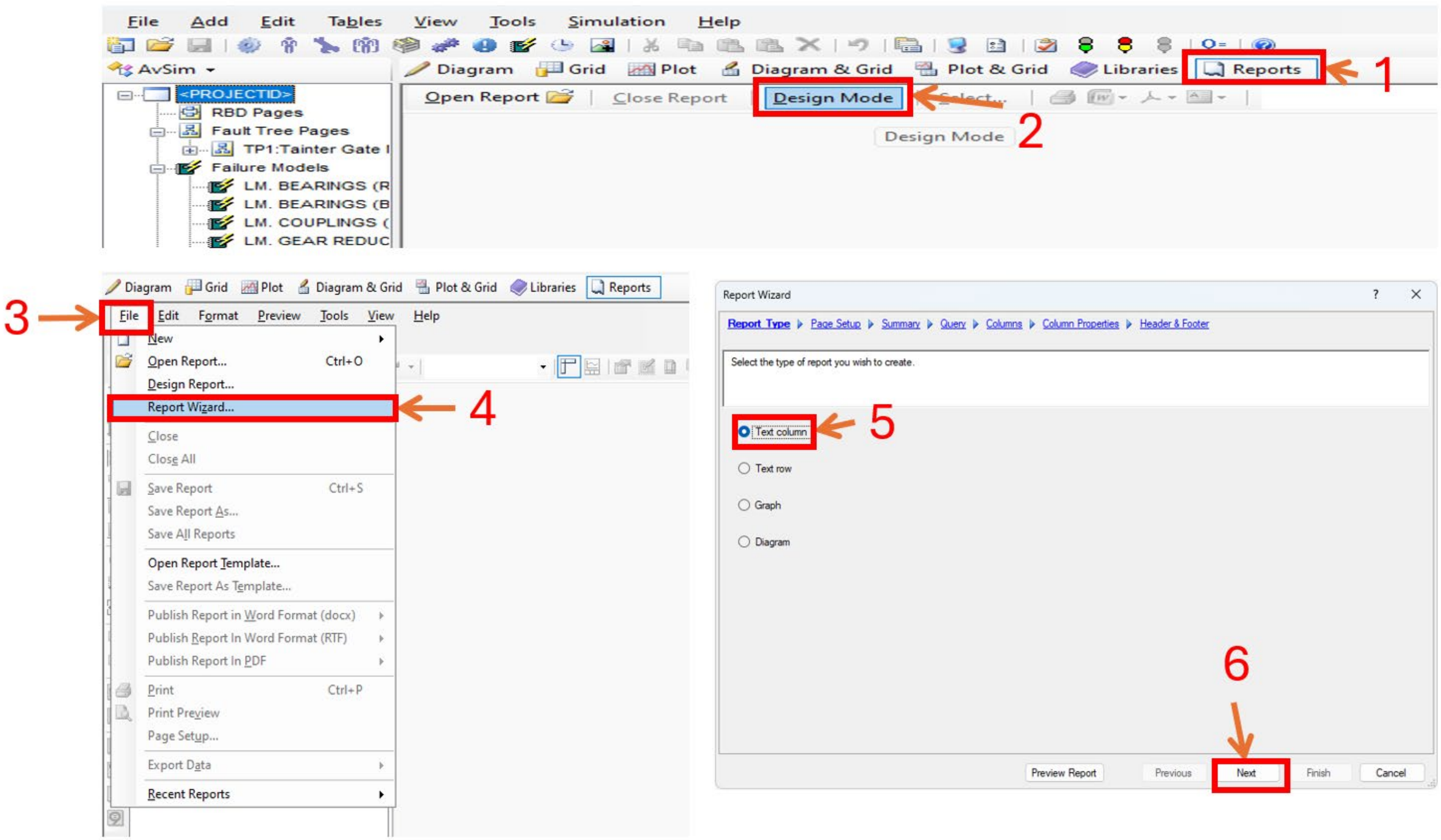


Figure C-24: Navigating to the Report Wizard and Choosing the Type of Report

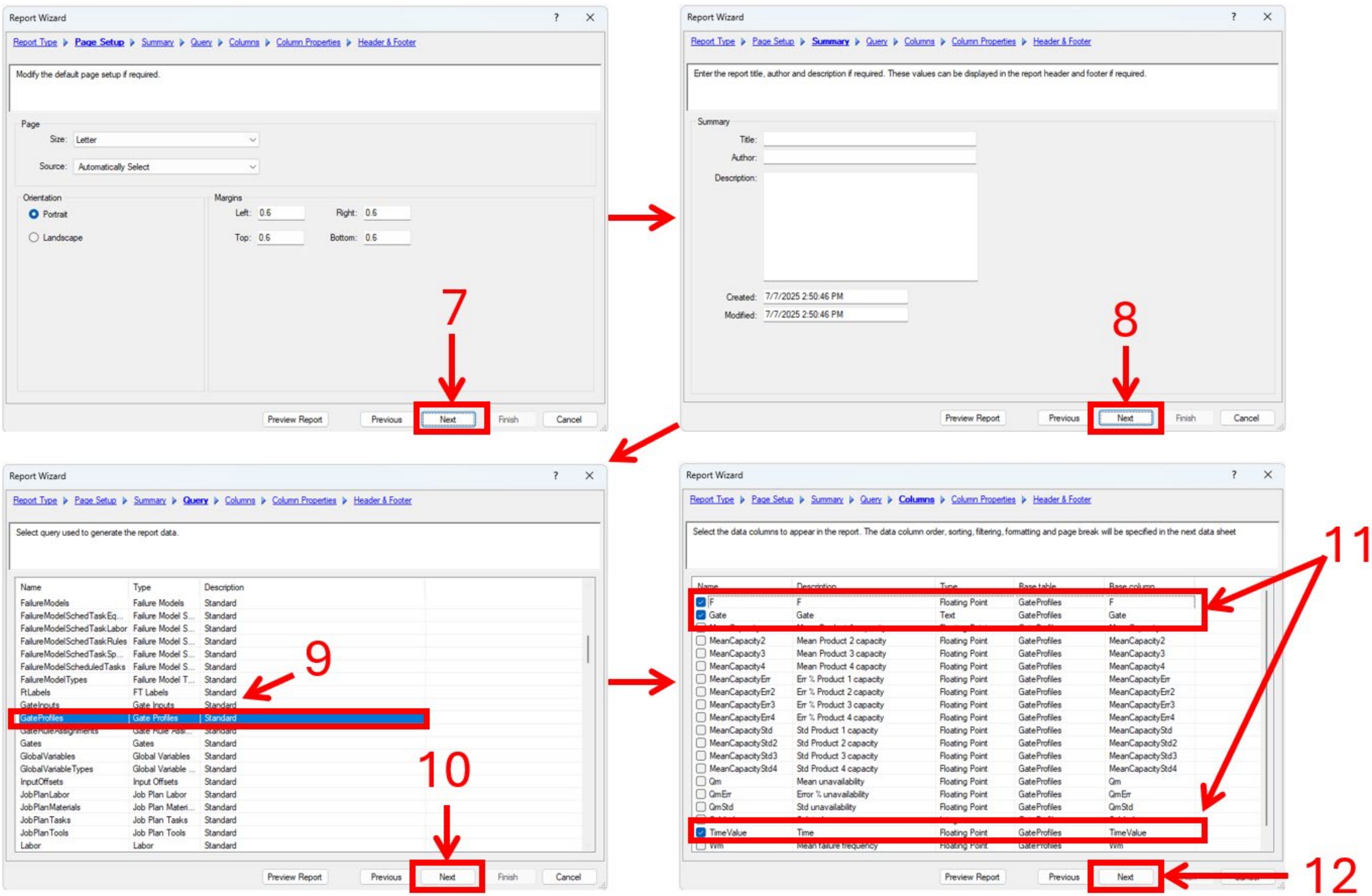


Figure C-25: Formatting the Report and Selecting the Data to Print

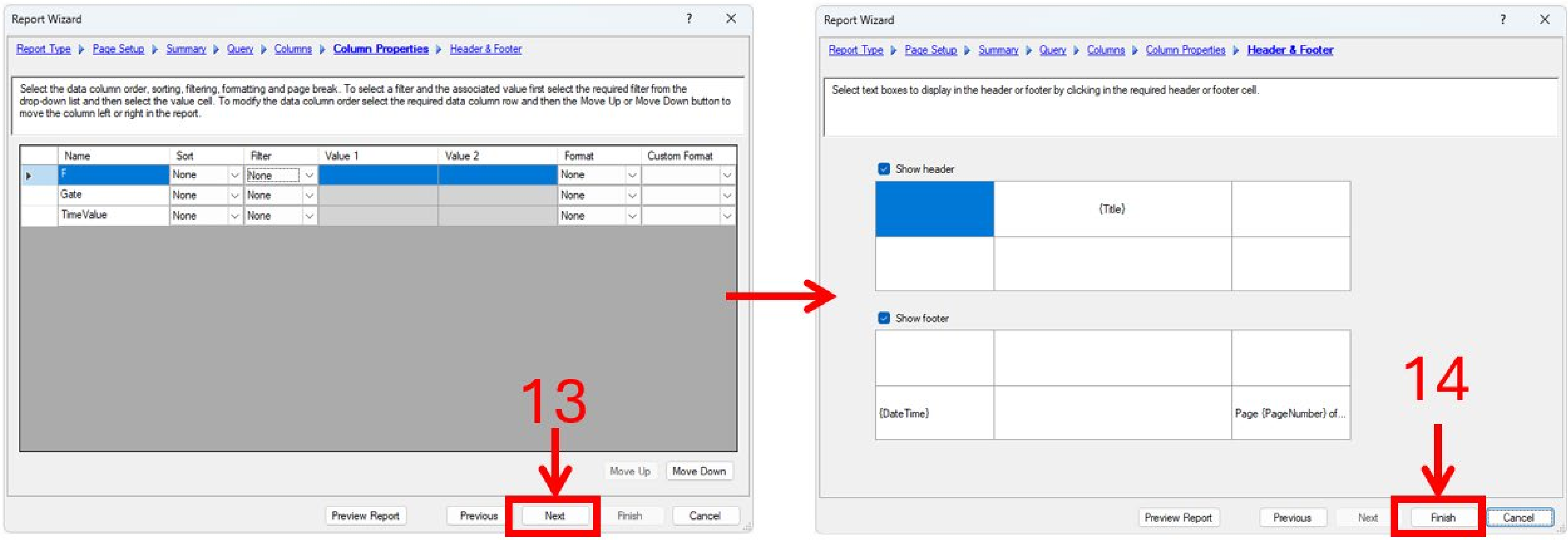


Figure C-26: Filtering the Results and Formatting the Report

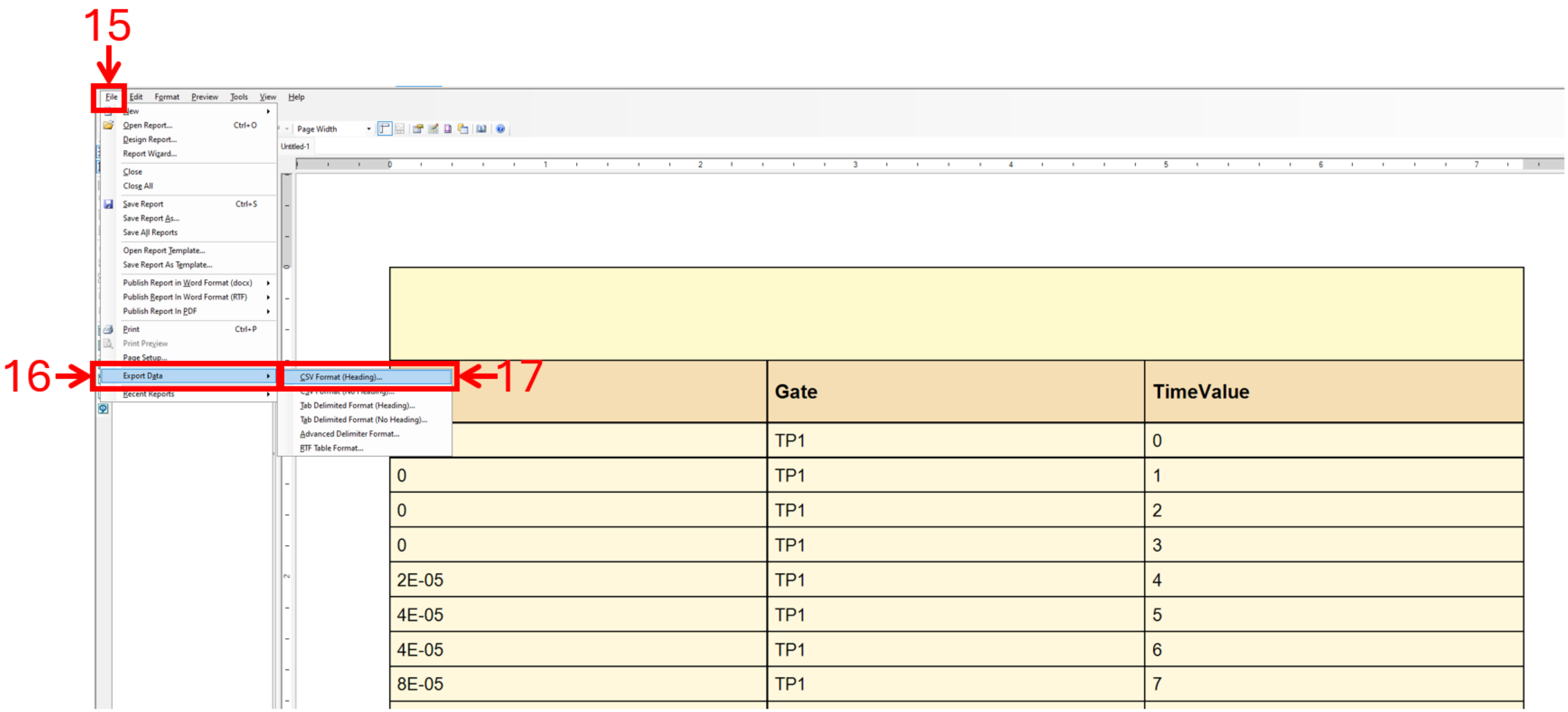


Figure C-27: Beginning to Export the Results

Figure C-28: Formatting the Export and Saving the Exported Data

The correct data must be selected for export, as shown in Figure C-25. Steps 9 through 12 in Figure C-25 show the selection of the correct data. Step 9 shows to select the "GateProfiles" query. Step 11 shows that the relevant columns from this query are "F", "Gate", and "TimeValue". The "GateProfiles" query shows how different variables change over time within the simulation. The "F" column is defined by Isograph as "… the probability that the system will have been out-of-service at least once during its lifetime. If outages can only be caused by failure, then this value represents the unreliability of the system". Because outages can only be caused by failure, this is the variable that will be relevant to the analysis. The "Gate" column defines the logical gate within the fault tree that are recorded for "TimeValue" and "F". The value of "Gate" corresponds to the gate ID for the different gates.

For the most efficient results, additional steps can be added in the interface where Step 13 is shown in Figure C-26. First, it is often useful to display the data in the order of Gate, then Time Value, then F. The filters applied should be "Greater Than 0" for F and "Equal To" for "Gate" with the value being the Gate ID for the Top Event. In this case, the Gate ID for the Top Event is TP1, as shown in Figure C-4. This will provide data that will be easier to move directly into the next step of the analysis. Figure C-29 shows the formatting for a typical results output.

Gate	TimeValue	F
TP1	4	2.00E-05
TP1	5	4.00E-05
TP1	6	4.00E-05
TP1	7	8.00E-05
TP1	8	0.00012
TP1	9	0.00014
TP1	10	0.00018

Figure C-29: Example Results Output

Step 7: Perform Post Processing and Hazard Curve Analysis — Once the results are exported to a .csv file, they can be transferred into an excel document for post processing and generation of the hazard function. The hazard function is the ultimate output of mechanical reliability analysis, and it is what is used in economic modeling to inform the benefits of various alternatives. The hazard function to be used is given by Eq. (1):

$$h(t;\beta,\alpha) = \frac{\beta}{\alpha}\left(\frac{t}{\alpha}\right)^{\beta-1} \qquad \textbf{Eq. (1)}$$

In Eq. (1), h represents the hazard function, which varies based on t, β, and α. In this instance, t represents time. β and α represent the two parameters of a Weibull distribution: the shape and scale parameters, respectively. Given that α and β are fixed values for a given Weibull distribution, h becomes a function of only t and is thus expressed as h(t). In order to find the hazard function from the data that was generated in AWB, the failure or unreliability distribution must have a two-parameter Weibull distribution fit to it. The following instructions outline the process to solve for α and β of the Weibull distribution that best fits the data.

Since the results of the analysis have been exported, the next step is to set up a spreadsheet document for the post processing analysis with the goal of solving for the α and β values that describe the Weibull distribution that best fits the data set. For the purposes of this example, this process was conducted in Microsoft Excel ®.

The first two columns of the spreadsheet should hold the Time Value and F variable, as outputted by AWB. In future steps, a natural logarithm will be applied to these values, so only values greater than 0 should be brought into the spreadsheet from the AWB data. The F variable outputted by AWB is meant to represent the probability of unreliability for the system. Because F is given at each timestep, and varies with time, this can be said to describe a Cumulative Distribution Function (CDF) for the unreliability of the system. Fundamental equations for Weibull distributions can be used to solve for the Weibull parameters that best fits the data.

The Cumulative Distribution Function (CDF) for unreliability of a Weibull distribution is given as:

$$F(t) = 1 - e^{-\left(\frac{t}{\alpha}\right)^{\beta}}$$ **Eq. (2)**

Here, the CDF is a function of time, t. Linearizing this equation, yields the linear form of the CDF:

$$\ln\left(ln\left(\frac{1}{1 - F(t)}\right)\right) = \beta \ln(t) - \beta \ln(\alpha)$$ **Eq. (3)**

Here, it can be observed that the linearized version of the equation takes the slope intercept form of a linear equation:

$$y = mx + b$$ **Eq. (4)**

where:

$$y = \ln\left(ln\left(\frac{1}{1 - F(t)}\right)\right)$$ **Eq. (5)**

ln(t) is the independent variable representing time, normally x in the slope intercept form of a linear equation. So:

$$x = \ln(t)$$ **Eq. (6)**

Because ln(t) is the independent variable, the coefficient modifying ln(t) becomes the slope of this line, normally represented as m in the slope intercept form. So:

$$m = \beta$$ **Eq. (7)**

b, the y-intercept of the line, is given by:

$$b = \beta \ln(\alpha)$$ **Eq. (8)**

α is found by its relationship to β and the y-intercept of the line, by isolating α from **Eq. (** 8 **)**:

$$\alpha = e^{-\left(\frac{b}{\beta}\right)}$$ **Eq. (9)**

Based on Eq. (6), the next column of the spreadsheet should contain the natural logarithm of t (the Time Value output from AWB) for each non-zero timestep from the model. This provides the independent variable, x, for the linearized function. The next column should isolate the dependent variable, y, by performing the operation as outlined in equation Eq. (5) for each non-zero output of F. *F(t)* from Eq. (5) is the output from AWB for the variable F in each given timestep from the simulation.

Now that the linearized function has been generated, the slope of that function is equal to the shape parameter for the Weibull distribution of best fit, as shown in Eq. (3), Eq. (4), and Eq. (7). Finding the slope of the linearized function is easily accomplished in Excel ® using the "SLOPE" function. To find the characteristic life, α, for the Weibull distribution of best fit, the y-intercept of the linearized function must be evaluated. This is easily accomplished in Excel ® using the "INTERCEPT" function. Next, α can be evaluated using Eq. (9). Because linear regression is used in Excel ® to find the slope and y-intercept of the linear line, the R^2 value for the trendline should be calculated to ensure quality of fit. This is easily accomplished in Excel ® using the "RSQ" function. The closer the R^2 value is to 1, the better the trendline fits the data.

Table C-1 shows a sample table of how the initial spreadsheet could be set up. Note that n represents the number of non-zero timesteps outputted by AWB and cells that have an "=" represent the mathematical operation or Excel ® command that would produce the desired value for that cell.

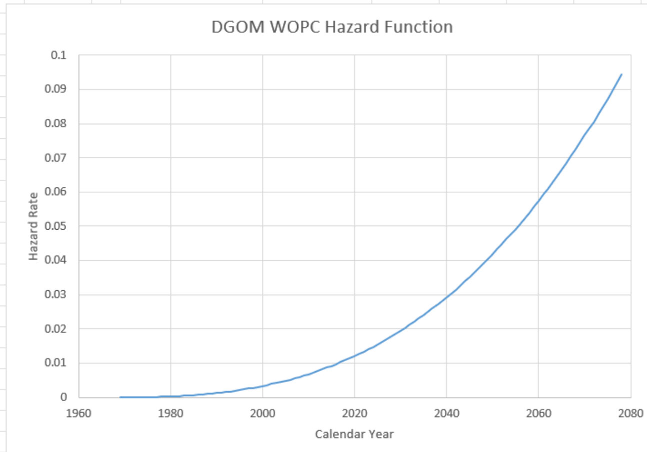
Table C-1: Sample Table for Spreadsheet Analysis

Time Value (t)	F	ln(t)	$\ln\left(ln\left(\frac{1}{1-F(t)}\right)\right)$	Weibull Parameters and Goodness of Fit	
t_1	F_1	$= \ln(t_1)$	$= \ln\left(ln\left(\frac{1}{1-F_1}\right)\right)$	ß:	$= SLOPE\left[\ln\left(ln\left(\frac{1}{1-F(t)}\right)\right), \ln(t)\right]$
…	…	…	…	α:	$= EXP\left[-\left(\frac{INTERCEPT\left[\ln\left(ln\left(\frac{1}{1-F(t)}\right)\right), \ln(t)\right]}{SLOPE\left[\ln\left(ln\left(\frac{1}{1-F(t)}\right)\right), \ln(t)\right]}\right)\right]$
t_n	F_n	$= \ln(t_n)$	$= \ln\left(ln\left(\frac{1}{1-F_n}\right)\right)$	R^2:	$= RSQ\left[\ln\left(ln\left(\frac{1}{1-F(t)}\right)\right), \ln(t)\right]$

With the two parameters for the Weibull distribution of best fit now estimated, the hazard function can be generated by substituting the estimated parameters into Eq. (1). The value of the hazard curve in each year of the study period is often useful for graphic comparison of with and without project conditions. Figure C-30 shows an example of how the spreadsheet was set up in Excel ® for graphic representation of the hazard function.

From Weibulls Tab:	
	2-Parameters
Shape parameter	3.86
Scale parameter	86.82

Calendar Year	Simulation Year	2-P Hazard Probabilty
1969	4	6.75955E-06
1970	5	1.27855E-05
1971	6	2.1522E-05
1972	7	3.34272E-05
1973	8	4.89487E-05
1974	9	6.85246E-05
1975	10	9.25853E-05
1976	11	0.000121554
1977	12	0.000155849
1978	13	0.000195882
1979	14	0.00024206
1980	15	0.000294786
1981	16	0.000354457
1982	17	0.00042147
1983	18	0.000496215
1984	19	0.000579079
1985	20	0.000670448
1986	21	0.000770704
1987	22	0.000880226
1988	23	0.000999389
1989	24	0.00112857
1990	25	0.001268138
1991	26	0.001418464
1992	27	0.001579915
1993	28	0.001752857
1994	29	0.001937653
1995	30	0.002134665
1996	31	0.002344252
1997	32	0.002566772
1998	33	0.002802582
1999	34	0.003052038
2000	35	0.003315491
2001	36	0.003593294
2002	37	0.003885798
2003	38	0.00419335
2004	39	0.0045163
2005	40	0.004854992
2006	41	0.005209773
2007	42	0.005580986
2008	43	0.005968973
2009	44	0.006374077



2-parameter equation hazard function:

The failure rate h (or hazard function) is given by:

$$h(t;\ \beta, \alpha) = \frac{\beta}{\alpha}\left(\frac{t}{\alpha}\right)^{\beta-1}$$

where β > 0 is the shape parameter and α > 0 is the scale parameter of the distribution. The hazard function can also be written as:

$$\frac{\beta t^{\beta-1}}{\alpha^{\beta}}$$

Figure C-30: Sample Spreadsheet Setup for Graphic Representation of Hazard Rate in Excel®

It should be noted that the units of the hazard function are failures per year and are not a percent probability of failure. Because of this, it is possible for the value of the hazard rate each year to be greater than 1, which would not be possible for other failure probabilities. The hazard function well approximates instantaneous failure probability each year when it is bound between 0 and 1.