ENGINEERING AND CONSTRUCTION BULLETIN

US Army Corps of Engineers

No. 2025-5 **Issuing Office:** CECW-EC **Issued:** 01 Apr 25 **Expires:** 01 Apr 27

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 a 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 a 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 bottom-up approach that start at the individual component level and roll up to an overall system level. 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 mean-time-to-failure (MTTF) in years, beta is the shape parameter of the distribution (e.g. normal distribution is a beta of about 4) and gamma is a shift in years of the start of the Weibull 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 MTTF. In addition, these models generally did not include either a duty factor, environmental factor, or load factors. Environmental and load 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 a 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. 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 or MTTF (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.

b. Selection of Duty Factors and Environmental/Stress Factors for Fault Tree and Reliability Block Diagrams**.** This attachment addresses how to apply duty factors and environmental and load factors to the components in the AWB fault tree model. Recommended values for duty factors and load factors 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.

//S//
THOMAS P. SMITH, P.E.
Director of Engineering and Construction
U.S. Army Corps of Engineers

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

ATTACHMENT A: Weibull Parameters Data Sources

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) or MTTF (Weibull alpha parameter) for mechanical components at both navigation (NAV) and flood risk management (FRM) projects and electrical components at NAV only.

2. Recommend that these are used for MRER FTA. Values for the Weibull beta (shape parameter) were not elicited as part of that study, but the user can assume a Beta between 3 to 4 to reflect wear and corrosion of ME components. Summary tables A-1 (mechanical) and A-2 (electrical) are presented below.

Table A-1 Mechanical Components CL at NAV and FRM Projects

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		80	100
Pins		35	70
Gear reducers			
	Worm	25	40
	Parallel	40	60
	Right angle	38	40
Open gearing			
	Spur	60	100
	Helical	38	100
	Bevel	40	50
	Rack	60	80
Brake	Electromechanical	45	60
Clutch	Slip	30	–
	Jaw	–	70
Wire ropes			

Table A-1 (con't) Mechanical Components CL at NAV and FRM Projects

Type	Component	Navigation Components CL (years)	Flood Reduction Components CL (years)
	Spiral plate	5	–
	Single/multiple sheave(s)	20	–
	Single Drum	28	–
	Round	–	50
	Flat	–	20
Wire rope drums		75	100
Wire rope sheaves		33	50
Chains	Roller	40	60
	Link	–	40
Chain sprocket		60	75
Miter gates			
	Sector arms	73	–
	Strut arms - buffered	35	–
	Strut arms - rigid	50	–
	Support roller	43	–
	Rack support beam	60	–
Valves			
	Bellcranks	78	–
	Crosshead/guide	73	–
	Strut	43	–
	Butterfly	–	50
	Ball	–	50
	Slide	–	50
	Knife	–	50
	Jet	–	50

Table A-1 (cont') Mechanical Components CL at NAV and FRM Projects

Type	Component	Navigation Components CL (years)	Flood Reduction Components CL (years)
Hydraulic cylinder		60	60
Control valves			
	Check	45	40
	Relief	40	40
	Directional		
	Manual	60	60
	Solenoid	40	40
	Proportional/throttle	40	40
Pumps			
	Fixed	50	60
	Variable	30	35
Hydraulic Motors			
	Fixed	50	–
	Variable	30	–
Piping		40	40
Hose		–	25
Misc Gate/Filling Emptying Valves			
Wheel assembly (rollers)		40	50
Pintles/bushings		30	–
Gudgeon pin/bushings		43	–
Trunnion pin/bushings		38	60
Strut spindle pin		25	–
Other Systems			
Tow haulage			
	Hydraulic	30	–
	Mechanical	48	–
Emptying filling			
	Butterfly	50	–
	Vertical lift	50	–
Gate connection (pins, cable, chain)		–	50
Grease/lube system		–	30
Actuators (screw type, limit torque)		–	50

Table A-2 Electrical Components CL at NAV Projects

Type	Component	Navigation Components CL (years)
Commercial power		4
Service transformer		55
Transfer switch	Automatic	30
	Manual	65
Switchgear		78
Circuit breakers		63
Power panelboard		78
Cables	Buried/submerged	60
	Duct/cable tray	80
	Portable/flexible	28
Bus duct		95
Switchboards		83
Motor control centers		83
Motor starters	Full voltage	63
	Reduced/variable	50
	VFD	35
PLC Systems		25
Selsyn motor		43
Traveling nut limit switch		65
Electric Motor	New or rebuilt	68
Standby generator set		50
DC rectifier brakes		35

3. **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”. Recommend using for FRM projects. The NAV FTA may not be as accurate since data is skewed to components that are not operated frequently. See Tables A-3 and A-4 below.

Table A-3 Mechanical Weibull Parameter from USACE FRM Projects

Components	Total inventoried	Weibull plotting		Bayesian (uniform prior)	
		Characteristic life: α	Shape parameter: β	Characteristic life: α	Shape parameter: β
Air compressor	51	47.22	10.37	66.94	8.94
Bearings (bronze bushing type)	2014	74.96	6.751	81.93	7.29
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 disp.)	422	75.42	4.245	80.16	3.93
Pumps (var. disp.)	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
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 Electrical Weibull Parameter from USACE FRM Projects

Components	Total inventoried	Weibull plotting		Bayesian (uniform prior)	
		Characteristic life: α	Shape parameter: β	Characteristic life: α	Shape parameter: β
Brakes (DC rectifier)	902	74.95	5.171	80.86	5.18
Control cables (fibre 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
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
Panel board	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

4. **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 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 is a summary table with Weibull information and component list for each category.

Table A-5 Controls Data – Groups 6 and 7

		Weibull Parameters		
	Period	Beta	Alpha	MTTF
	(years)			(years)
Control A - #6	50	3.3	35.5	35.5
Control B - #7	35	3	20	20

Controls A
6

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

Controls B
7

PLC Systems
HMI/PC Hardware
Software
Control Cable
Power Cable
Panel Cabinets
I/O racks
Displays
Alarms

SCADA
Communication Infrastructure
Remote Terminal Units
Controllers
Power Cable
Communication Cable
Panel Cabinets
Supervisory PC Based Hardware
Software
I/O Devices
Displays
Alarms

Integrated Interlock Systems
Control Panels
Displays/Indicators
Control Cable
Communication Cable
By-Pass Switches
Interlocking Devices

Misc. Solid State Controls
Photooptic controls
Transfer Switches

Table A-6 Electrical Data – Groups 11 to 15

		Weibull Parameters		
	Period	Beta	Alpha	MTTF
	(years)			(years)
Electrical A - #11	60	4.7	47	47
Electrical B - #12	60	2.9	45	45
Electrical C - #13	50	4.5	43	43
Electrical D - #14	40	4.5	33	33
Electrical E - #15	60	3.5	82	82

Electrical A
11

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
12

Operating - Electric
Electric Motors
Electric Brakes
Motor Starters
Speed Drives
Contactors
Control Relays

Electrical C
13

Lighting
Light Fixtures
Power Cable

Electrical D
14

Emergency Power System
Generator Set
Manual Transfer Switches
Generator Fueling System

Electrical E
15

Grounding
Ground Mats
Lightning Protection

Table A-7 Operating Equipment Data – Groups 23 to 28

		Weibull Parameters		
	Period	Beta	Alpha	MTTF
	(years)			(years)
Operating Equipment A #23	75	4.1	60	60
Operating Equipment B #24	50	3.4	35	35
Operating Equipment C #25	60	3.4	51	51
Operating Equipment D #26	50	3.3	35.5	35.5
Operating Equipment E #27	40	3.6	31	31
Operating Equipment F #28	50	3.9	46	46

Operating Equipment A
23

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
24

Mechanical
Brakes
Bearings
Bushings
Pins
Springs

Operating Equipment C
25

Hydraulic
Hyd. Cylinders
Hyd. Motors
Hyd. Pumps
Hyd. Power Units
Flow Control Valves
Valves
Hyd. Reservoirs
Accumulators

Water Driven Hydraullic
Control Gates/Wickets
Turbine
Pump

Misc. Hydraulic Equipment
Filters
Hyd. Piping
Hyd. Hosing

Operating Equipment D
26

Water Pumps
Dewatering Pumps
Raw Water Pumps
Sump Pumps

Operating Equipment E
27

Compressed Air
Air Compressors
Air Dryers
Valves
Regulators
Gauges

Steam System
Boilers
Water Intakes
Valves
Gages
Controls

Operating Equipment F
28

Misc.
Seals
Fenders
Cathodic Protection Systems
Dogging Mechanisms
Automatic Lubrication Systems

ATTACHMENT B: Duty and Environmental Factors

a. Duty Cycles. The mission or function of the system should address the duty cycle or period of operation. For example, miter gate equipment is considered to have a negligible failure rate during periods of nonoperation. The failure rate can be modified by a duty cycle factor. The duty cycle factor is the ratio of actual operating time to total mission time t. For example, the equation:

$$R(t) = e^{-.td}$$

is the exponential failure rate distribution with a duty factor d. The duty factor for lock mechanical equipment is directly related to the number of lockages or hard operations that occur at a facility. The number of lockages may vary over time, and hence the duty factor may vary. In this example, the lockages or cycles increase with time.

The duty factor, d, is calculated for each year as follows: For example, in year 5, the lock performs 11,799 open/close cycles. Assuming the operating time of an open or close operation is 120 seconds (or 240 seconds per open/close cycle) and using a total mission time of 8760 hours per year then the duty factor can be calculated as follows:

Operating time = (240*11,799)/3600
= 786.6 operational hours/year

d = 786.6/8760 hours/year
d = 0.0898

The Weibull reliability function from the main text for the components becomes

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

Where time t is in years. The Weibull hazard function then becomes

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

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

1. 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.

2. 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. An apportionment value of 50% indicates that the component ages at only half the normal rate when it is non-operational.

These factors are part of the Failure Models in AWB for each component shown in Figure B.1 below as 10 percent of the duty cycles. This allows the failure rate and age to be reduced to a duty factor of 10 percent during the AWB simulations.

Figure B.1 Duty Factors in AWB

Failure Models ▾ Basic data ▾ All rows ▾

ID	Description	Failure distribution	Failure Eta1	Failure Beta1	Failure Gamma1	Non-operating failure apportionment	Non-operating ageing apportionment	Dormant failure
ANTIFRICTION B...		Weibull	40	4	0	10	10	☐
BRAKE		Weibull	45	4	0	10	10	☐
COUPLING	COUPLING	Weibull	50	4	0	10	10	☐
GEAR REDUCER		Weibull	38	4	0	10	10	☐
PLAIN BRONZE ...		Weibull	40	4	0	10	10	☐
SHAFTS		Weibull	80	4	0	10	10	☐
SPUR GEARS		Weibull	60	4	0	10	10	☐

b. Environmental Conditions. Load factors may be assigned to individual blocks of the fault tree in AWB. The load factor allows users to model additional or reduced stress conditions during different operational phases. Default value in AWB is 1. In addition, the warm Standby option also needs to be active for the component in the AWB fault tree model. 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:

$$MTTF = MTTF_{Normal}/\text{Load Factor}$$

c. Environmental conditions must be defined for the ambient service of the equipment. An approximate approach multiplies failure data by various K factors to relate the data to other conditions of environment and stress where K is the environmental factor adjustment coefficient used to represent component stress levels altered by environmental conditions. Typical K factors are given in Table B-1 where K1 relates to the general environment of operation, K2 to the specific rating or stress of the component, and K3 to the general effect of temperature. The equipment on the lock is exposed to an outdoor marine environment. For this example, a K1 factor of 2 is used and K2 and K3 are 1.0. Recommended values are 1.0 for K1, K2 and K3.

Table B-1 Environmental Condition for Load Factors in AWB

General Environmental Condition	K_1
Ideal, static conditions	0.1
Vibration-free, controlled environment	0.5
General purpose ground based	1.0
Ship	2.0
Road	3.0
Rail	4.0
Air	10.0
Missile	100.0
Stress Rating	
Percentage of component nominal rating	K_2
140	4.0
120	2.0
100	1.0
80	0.6
60	0.3
40	0.2
20	0.1
Temperature	
Component temperature (degrees C)	K_3
0	1.0
20	1.0
40	1.3
60	2.0
80	4.0
100	10.0
120	30.0

These load factors are part of the Primary Events in AWB for each component shown in Figure B.2 below. This allows the load factor to reduce the MTTF of 2 as shown below during the AWB simulations

Figure B.2 Load Factors in AWB

Primary Events ▾ Basic data ▾ All rows ▾

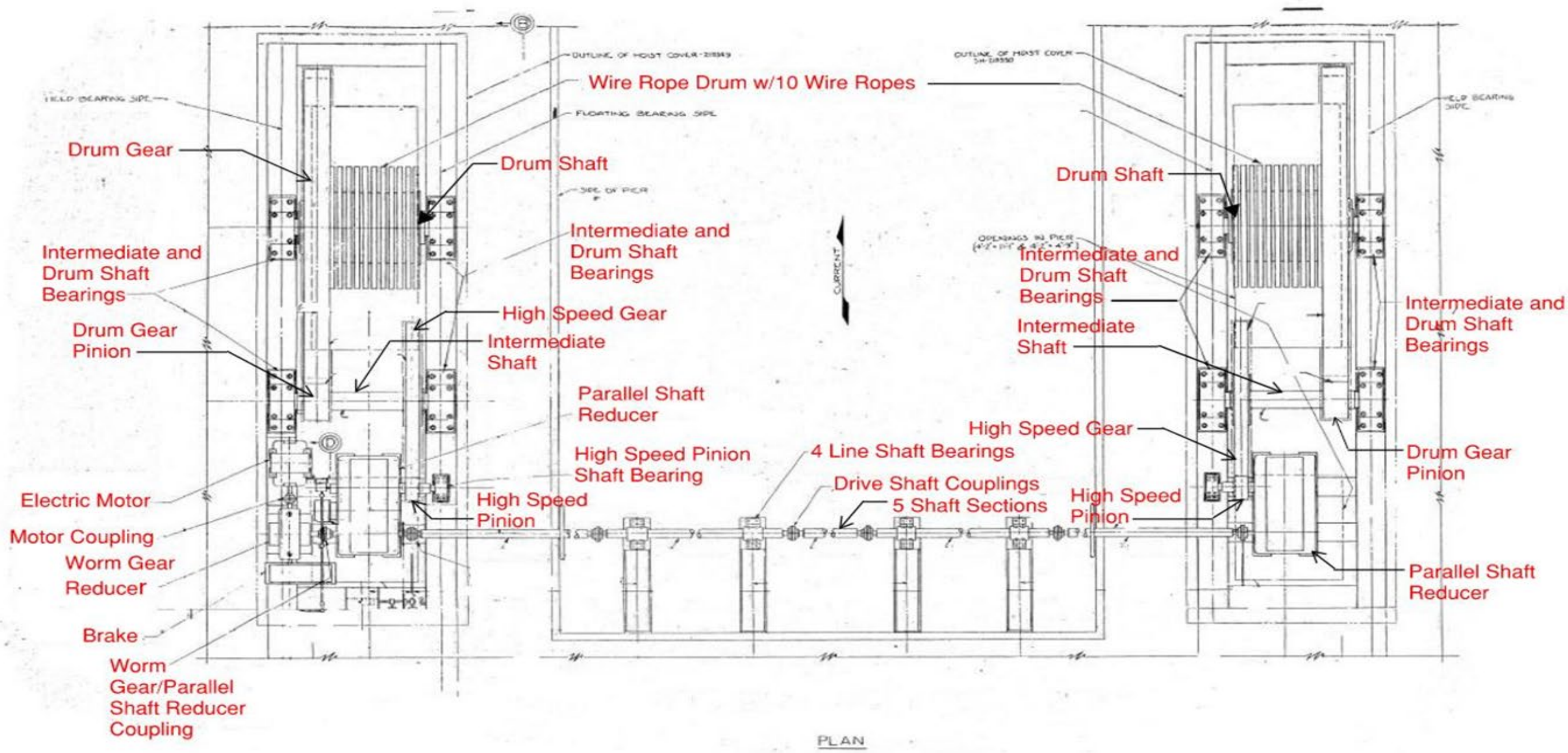
ID	Description	Type	Failure Model	Logic mode	Maximum capacity	Initial age	Switching delay	Load factor	Non-maintainable	Use standby times to failure	Standby mode
EV2	Coupling Failure	Basic	LM. COUPLINGS ...	Probabilistic	100	0	0	2	☐	☑	Warm
EV3	Worm Gear Reducer ...	Basic	DM GEARS (RIG...	Probabilistic	100	0	0	2	☐	☑	Warm
EV11	Pinion #1 Failure	Basic	DM HIGHER SPEE...	Probabilistic	100	0	0	2	☐	☑	Warm
EV12	Gear #1 Failure	Basic	DM HIGHER SPEE...	Probabilistic	100	0	0	2	☐	☑	Warm
EV13	Pinion #2 Failure	Basic	DM. GEARS (SP...	Probabilistic	100	0	0	2	☐	☑	Warm
EV14	Gear #2 Failure	Basic	DM. GEARS (SE...	Probabilistic	Probabilistic	0	0	2	☐	☑	Warm
EV15	Pinion #3 Failure	Basic	DM. GEARS (SP...	Probabilistic	100	0	0	2	☐	☑	Warm
EV16	Gear #3 Failure	Basic	DM. GEARS (SE...	Probabilistic	100	0	0	2	☐	☑	Warm
EV17	Shaft Failure	Basic	LM. ROTATING S...	Probabilistic	100	0	0	2	☐	☑	Warm
EV18	Chain Sprocket Failure	Basic	DM. CHAIN (SPR...	Probabilistic	100	0	0	2	☐	☑	Warm
EV19	Chain Failure	Basic	DM. CHAIN (ROL...	Probabilistic	100	0	0	2	☐	☑	Warm
EV20	Brake Failure	Basic	DM. BRAKE (SPR...	Probabilistic	100	0	0	2	☐	☑	Warm

ATTACHMENT C: Example Application of Fault Tree for Navigation Dam Operating Equipment

The following example shows the basic steps for obtaining system hazard function parameters and is based on Tainter gate operating machinery commonly used on navigation dams. The first page includes a plan view of the machinery with the major components identified which are included in a fault tree.

Following the plan, the fault tree is presented which is based on the machinery arrangement. The fault tree was created using Availability Workbench v.5.0. It is not the intention of this example to provide guidance or instruction in fault tree analysis. For that, other resources or training should be consulted.

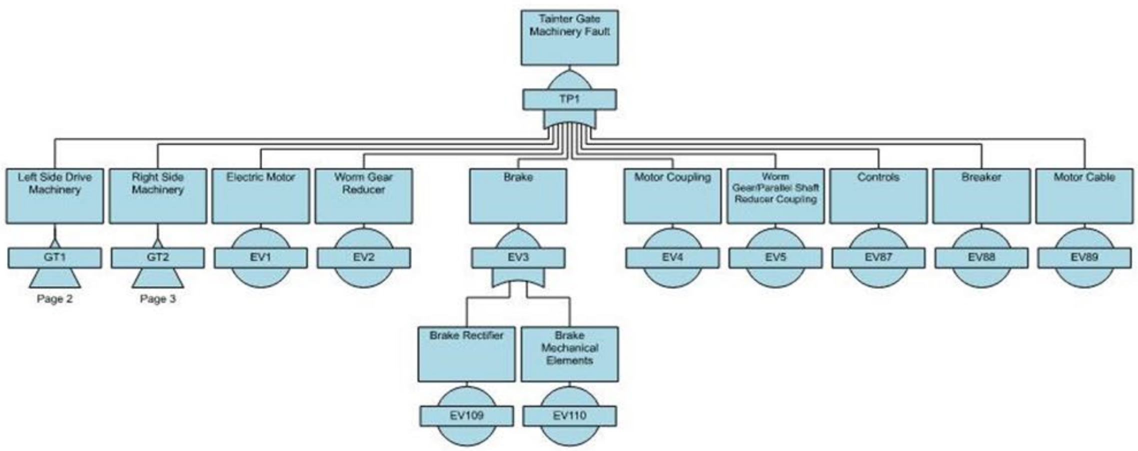
After the 9 pages of the fault tree diagram, individual screen shots showing where to enter recommended parameters are included. This fault tree represents the Without Project Condition, but it can easily be adapted for various with project scenarios by adjusting the project age and/or individual component location parameters. The final page is a print of the Excel sheet with the exported Unreliability or Cumulative Distribution Function (CDF) from Availability Workbench. By linearizing the CDF as described on the sheet, the Weibull parameters for the hazard function are found.


Wire Rope Drum w/10 Wire Ropes
Drum Gear
Drum Shaft
Intermediate and Drum Shaft Bearings
Intermediate and Drum Shaft Bearings
High Speed Gear
Drum Gear Pinion
Intermediate Shaft
Parallel Shaft Reducer
High Speed Pinion Shaft Bearing
Electric Motor
High Speed Pinion
Motor Coupling
Worm Gear Reducer
Brake
Worm Gear/Parallel Shaft Reducer Coupling
4 Line Shaft Bearings
Drive Shaft Couplings
5 Shaft Sections
CURRENT
Drum Shaft
Intermediate and Drum Shaft Bearings
Intermediate Shaft
Intermediate and Drum Shaft Bearings
High Speed Gear
Drum Gear Pinion
High Speed Pinion
Parallel Shaft Reducer
PLAN

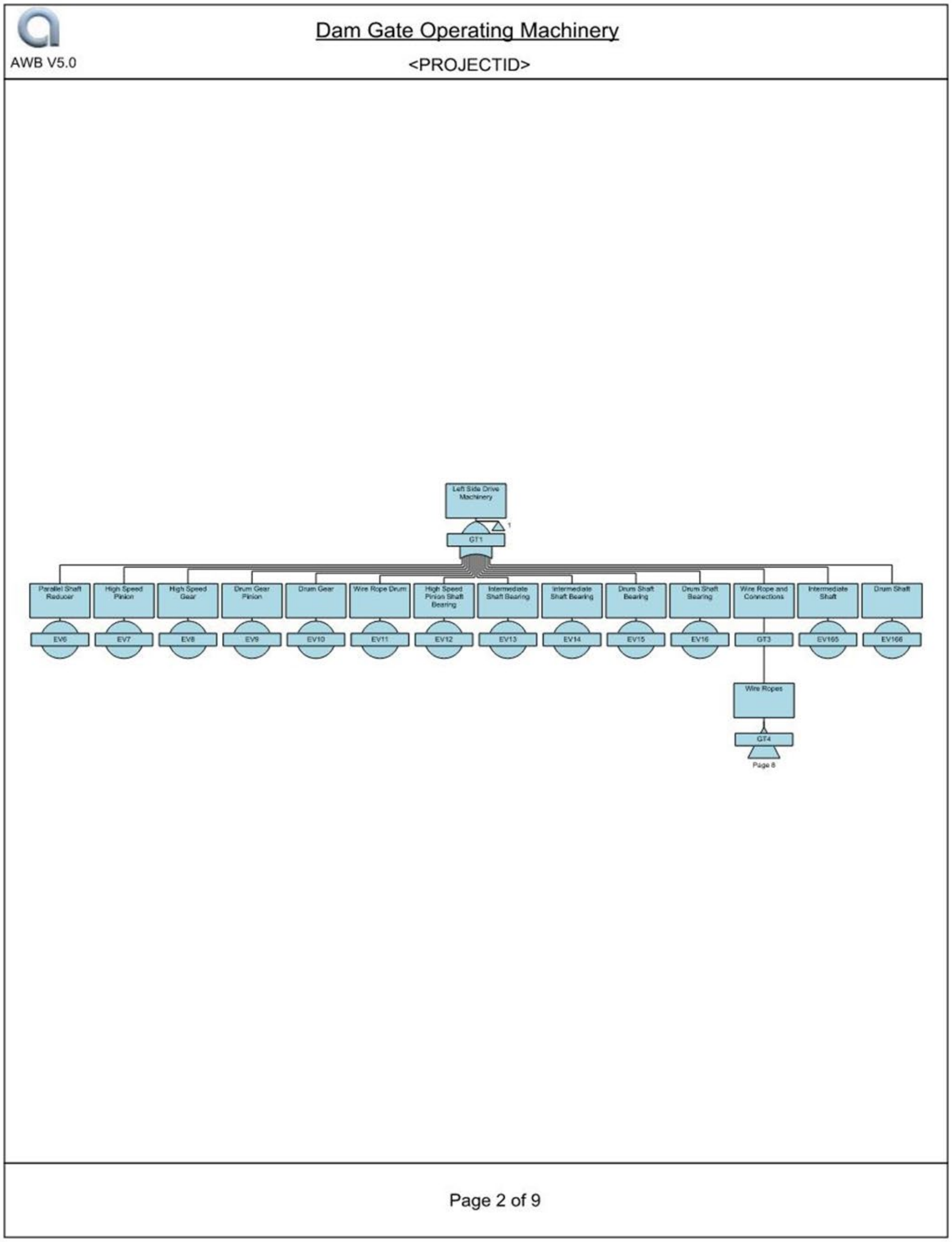
AWB V5.0

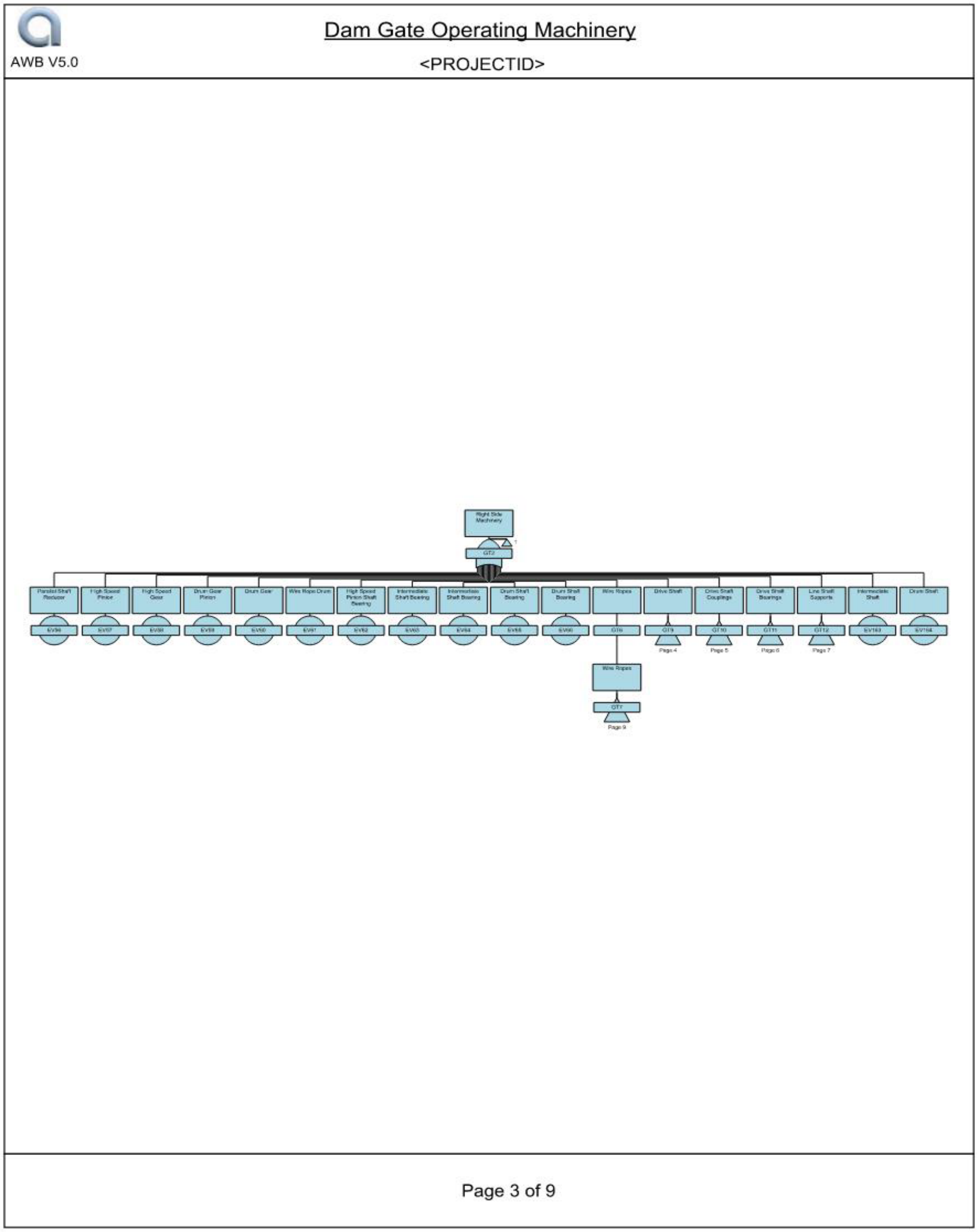
Dam Gate Operating Machinery

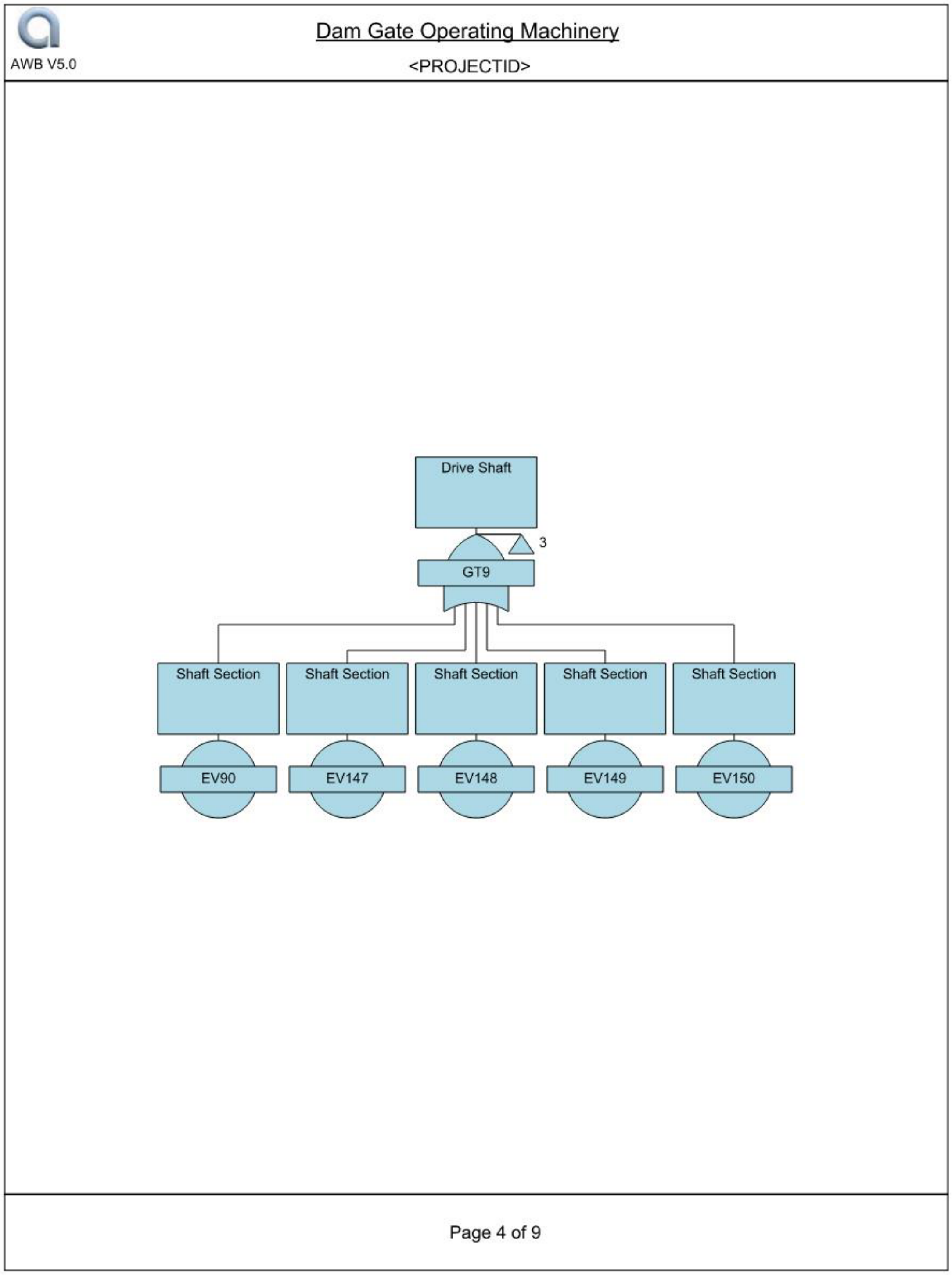
<PROJECTID>

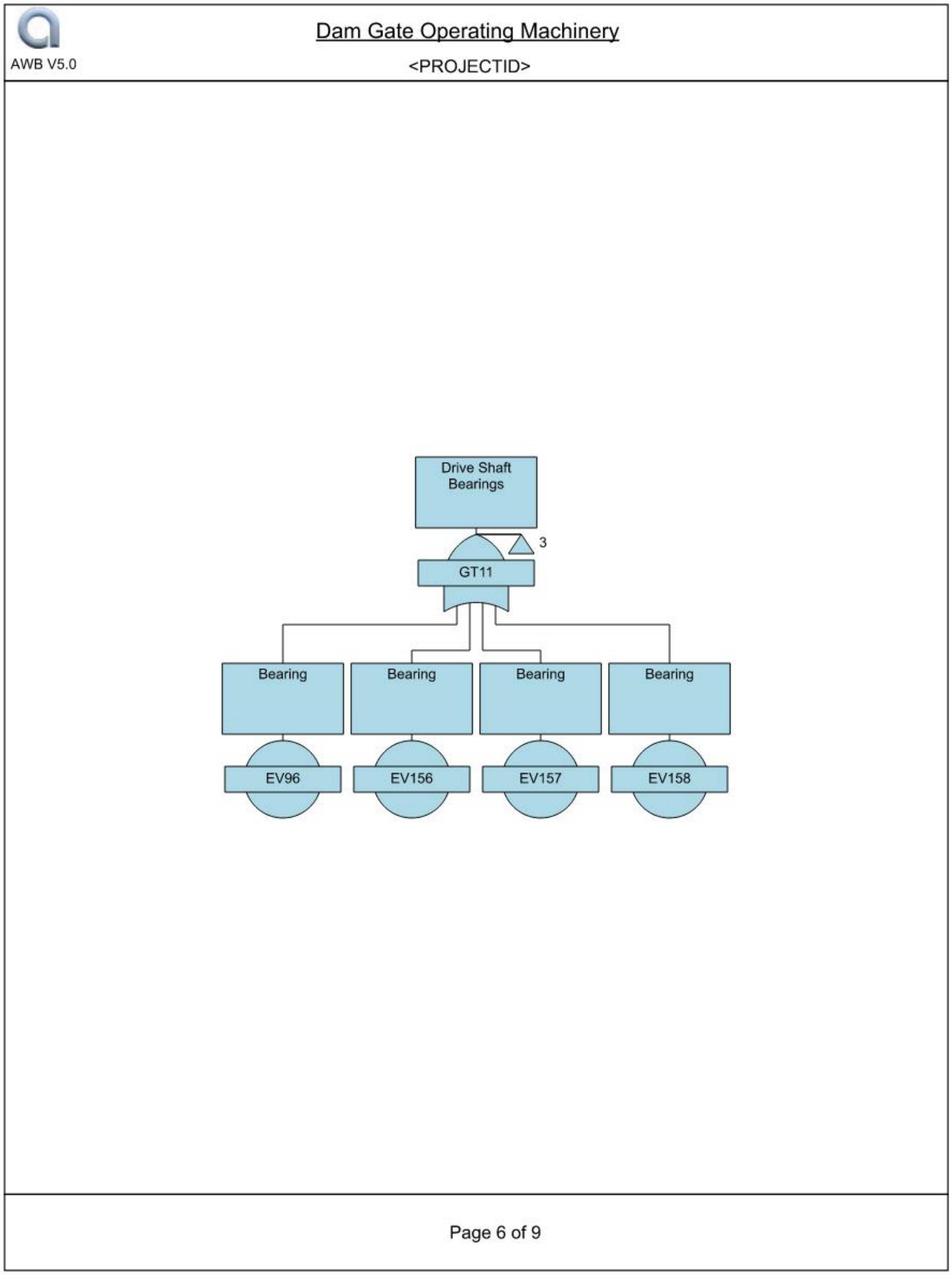


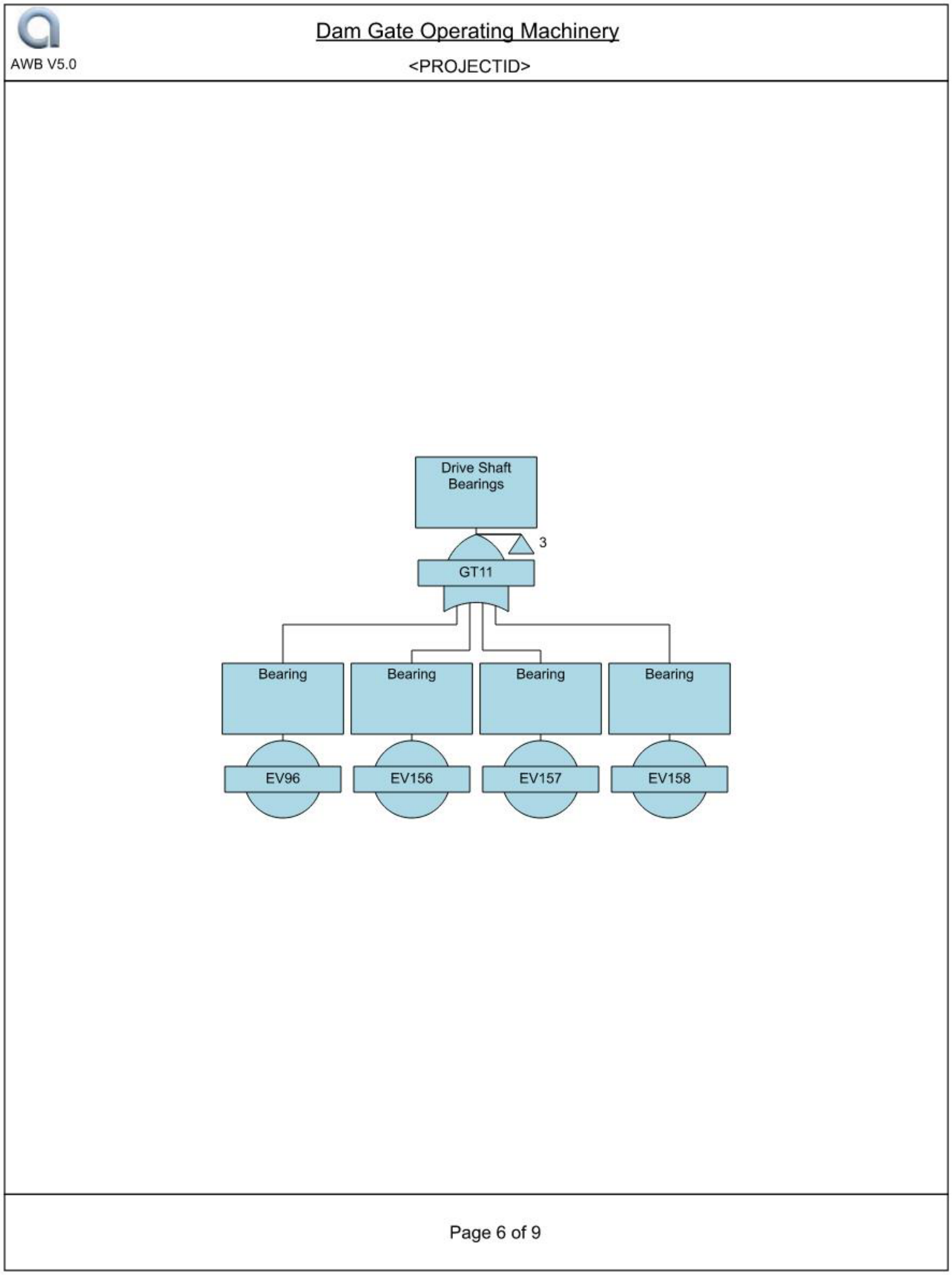
Page 1 of 9

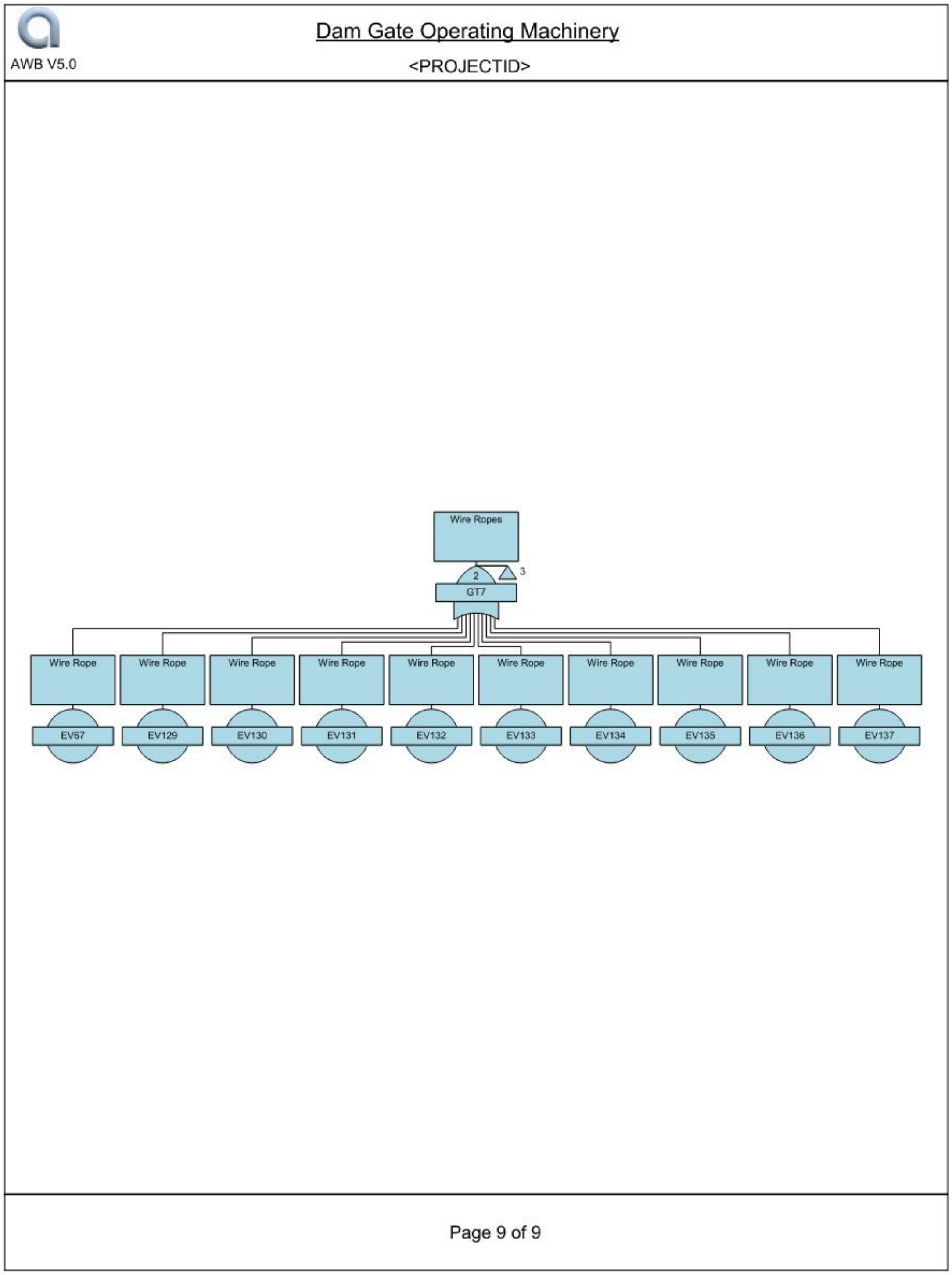

AWB V5.0
Dam Gate Operating Machinery
<PROJECTID>
Left Side Drive Machinery
GT1
1
Parallel Shaft Reducer
EV6
High Speed Pinion
EV7
High Speed Gear
EV8
Drum Gear Pinion
EV9
Drum Gear
EV10
Wire Rope Drum
EV11
High Speed Pinion Shaft Bearing
EV12
Intermediate Shaft Bearing
EV13
Intermediate Shaft Bearing
EV14
Drum Shaft Bearing
EV15
Drum Shaft Bearing
EV16
Wire Rope and Connections
GT3
Intermediate Shaft
EV165
Drum Shaft
EV166
Wire Ropes
GT4
Page 8
Page 2 of 9

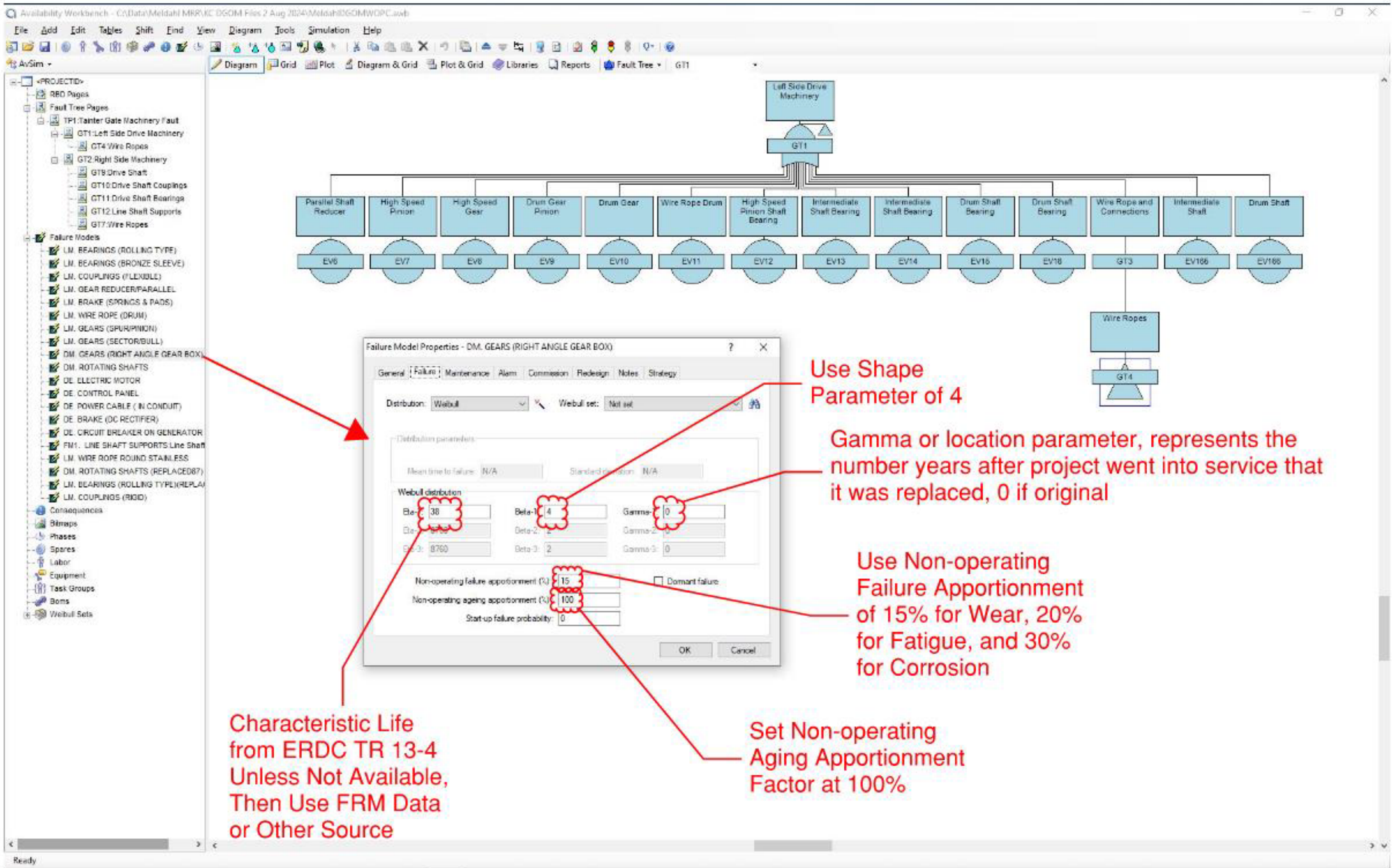

AWB V5.0
Dam Gate Operating Machinery
<PROJECTID>
Right Side Machinery
GT2
Parallel Shaft Reducer
High Speed Pinion
High Speed Gear
Drum Gear Pinion
Drum Gear
Wire Rope Drum
High Speed Pinion Shaft Bearing
Intermediate Shaft Bearing
Intermediate Shaft Bearing
Drum Shaft Bearing
Drum Shaft Bearing
Wire Ropes
Drive Shaft
Drive Shaft Couplings
Drive Shaft Bearings
Line Shaft Supports
Intermediate Shaft
Drum Shaft
GT9
GT10
GT11
GT12
EV103
EV104
Page 4
Page 5
Page 6
Page 7
Wire Ropes
GT7
Page 9
Page 3 of 9

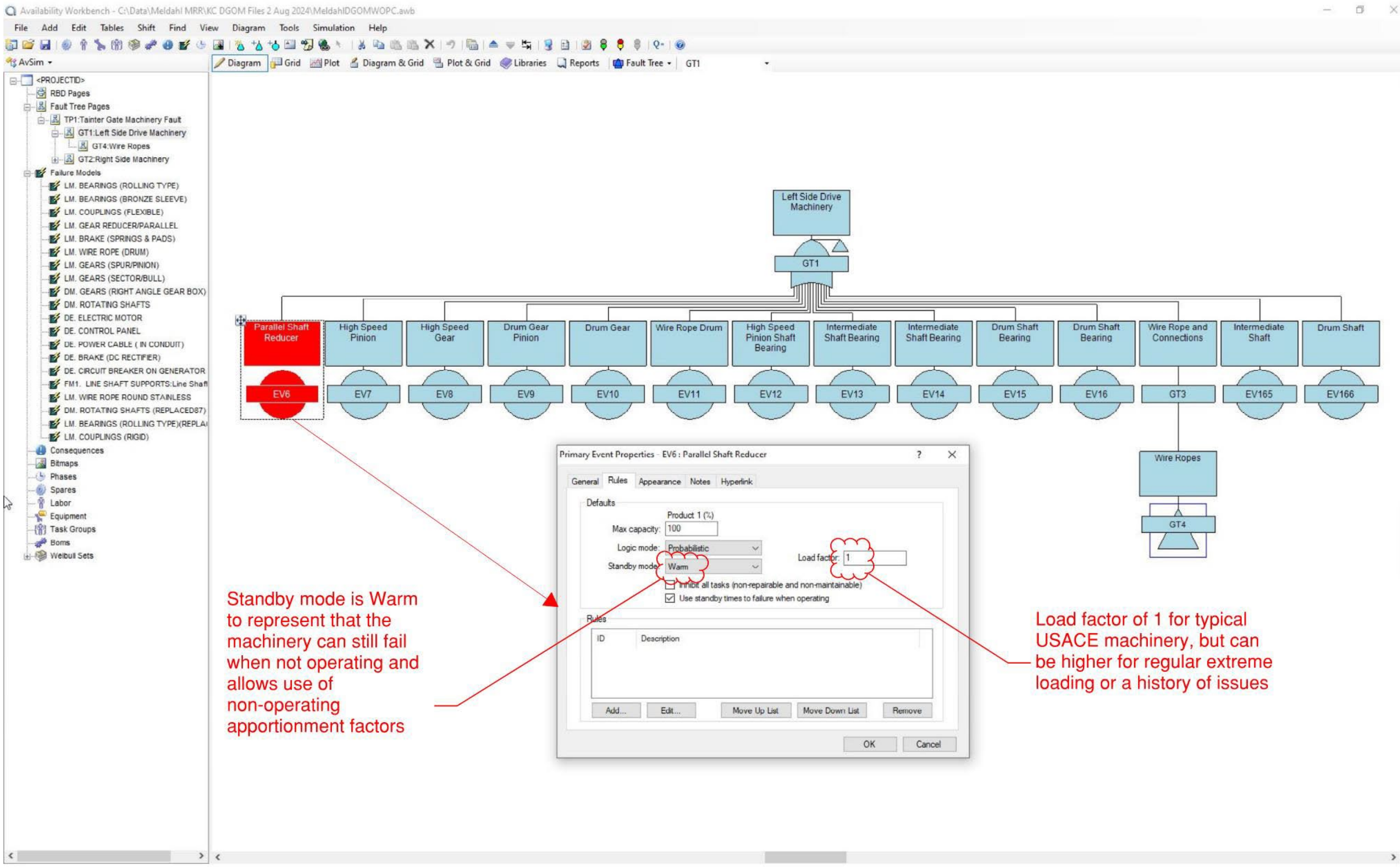

AWB V5.0
Dam Gate Operating Machinery
<PROJECTID>
Drive Shaft
3
GT9
Shaft Section
Shaft Section
Shaft Section
Shaft Section
Shaft Section
EV90
EV147
EV148
EV149
EV150
Page 4 of 9

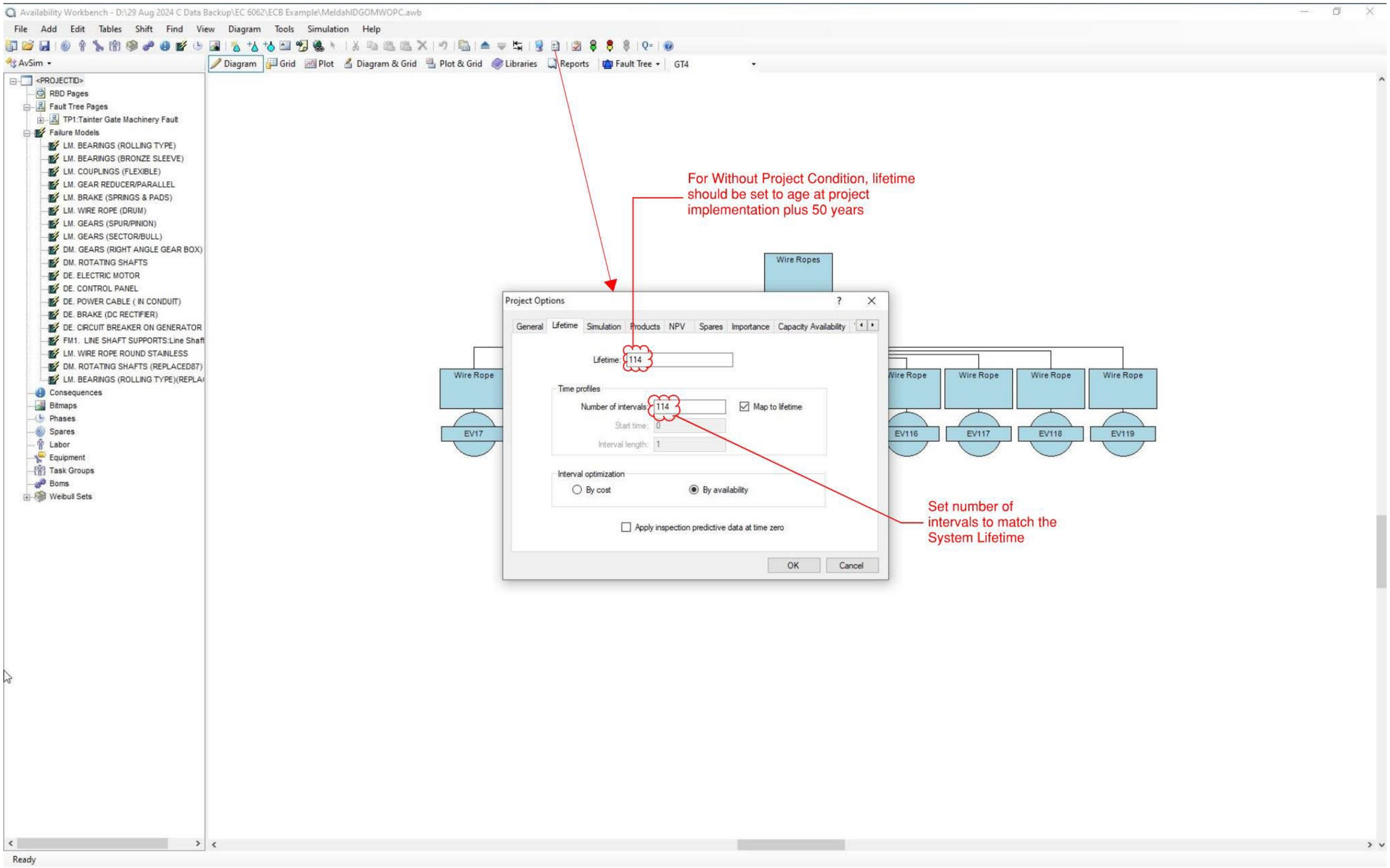

AWB V5.0
Dam Gate Operating Machinery
<PROJECTID>
Drive Shaft Bearings
3
GT11
Bearing
Bearing
Bearing
Bearing
EV96
EV156
EV157
EV158
Page 6 of 9

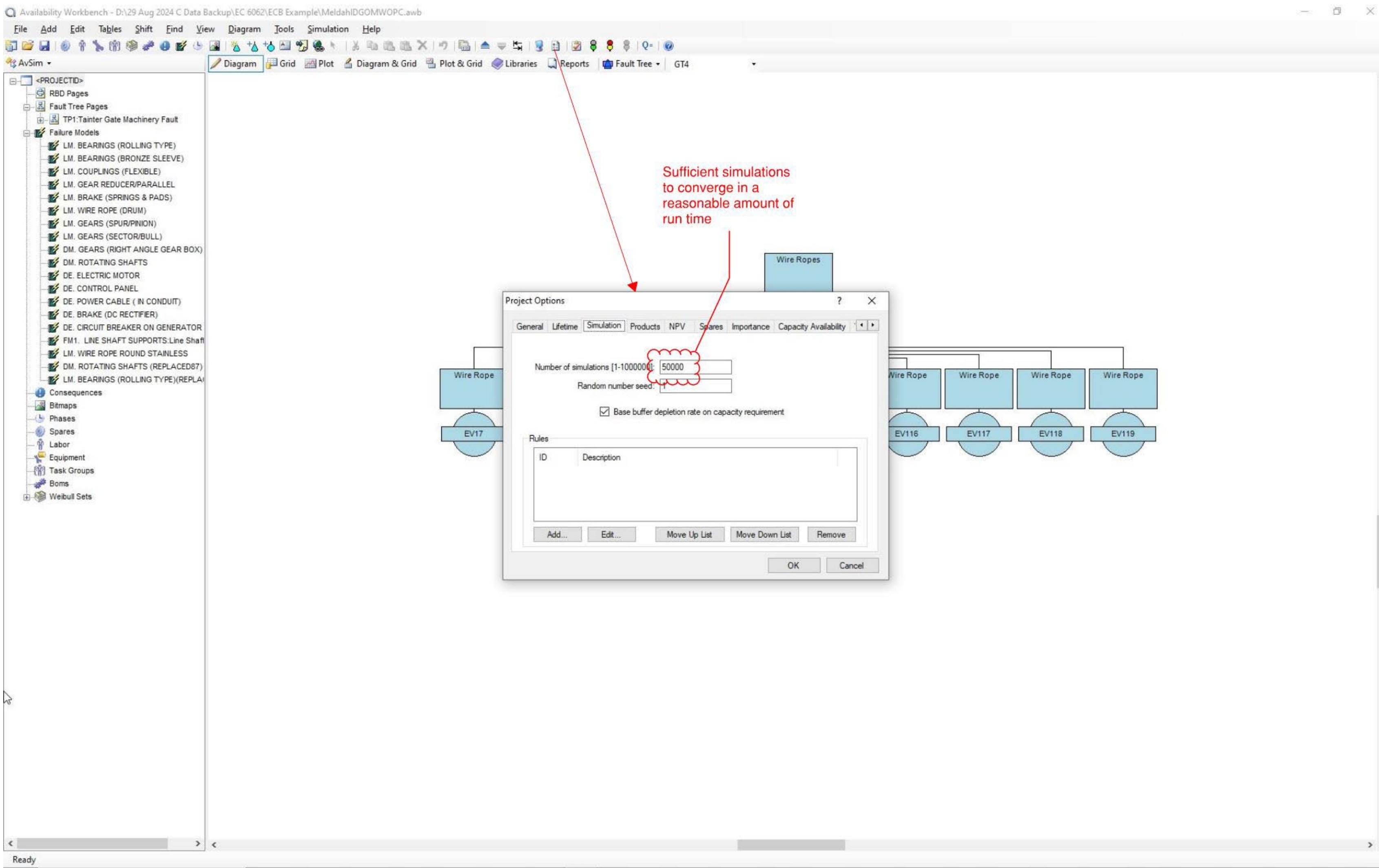

AWB V5.0
Dam Gate Operating Machinery
<PROJECTID>
Drive Shaft Bearings
3
GT11
Bearing
Bearing
Bearing
Bearing
EV96
EV156
EV157
EV158
Page 6 of 9

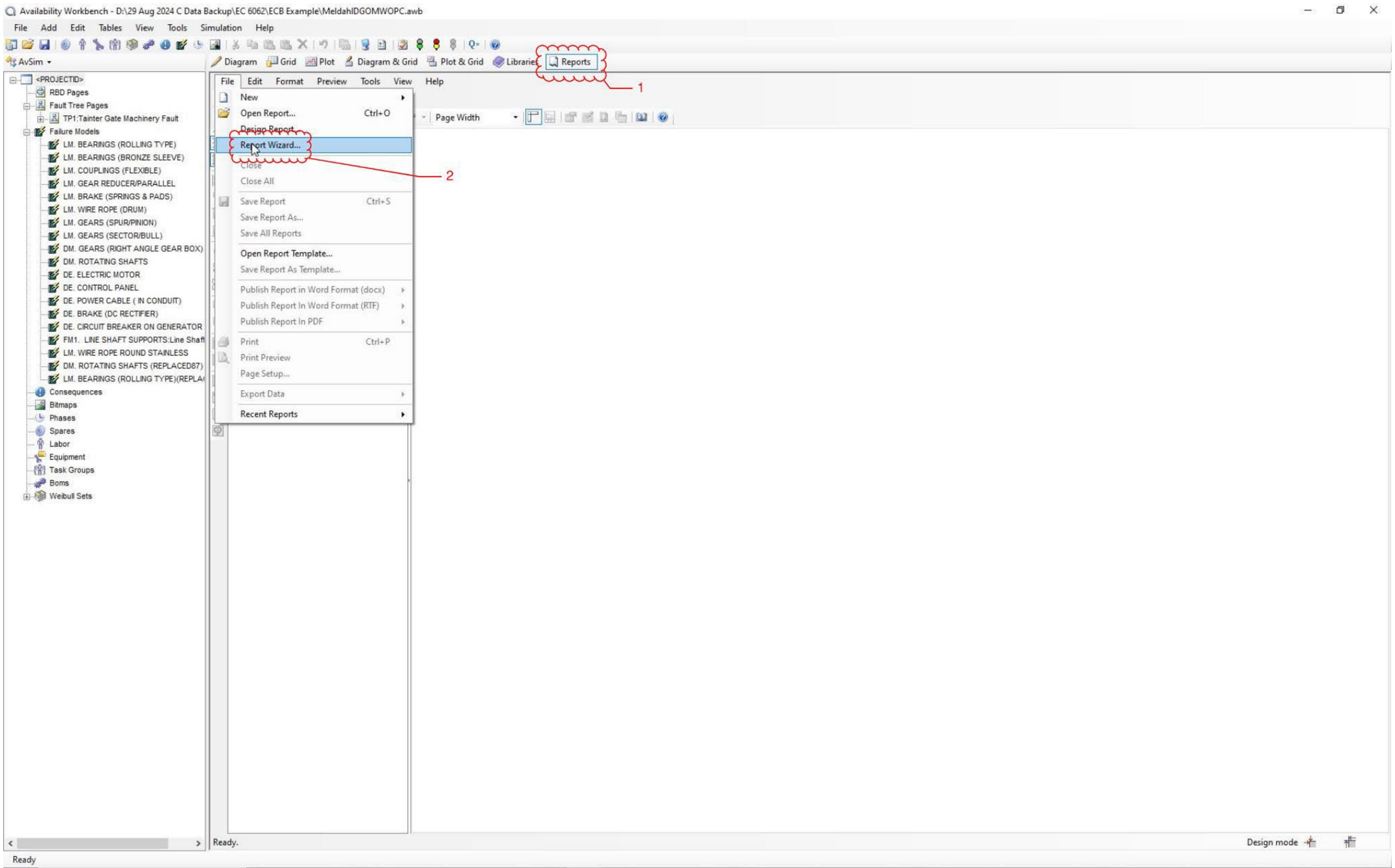

AWB V5.0
Dam Gate Operating Machinery
<PROJECTID>
Wire Ropes
2
3
GT7
Wire Rope
Wire Rope
Wire Rope
Wire Rope
Wire Rope
Wire Rope
Wire Rope
Wire Rope
Wire Rope
Wire Rope
EV67
EV129
EV130
EV131
EV132
EV133
EV134
EV135
EV136
EV137
Page 9 of 9

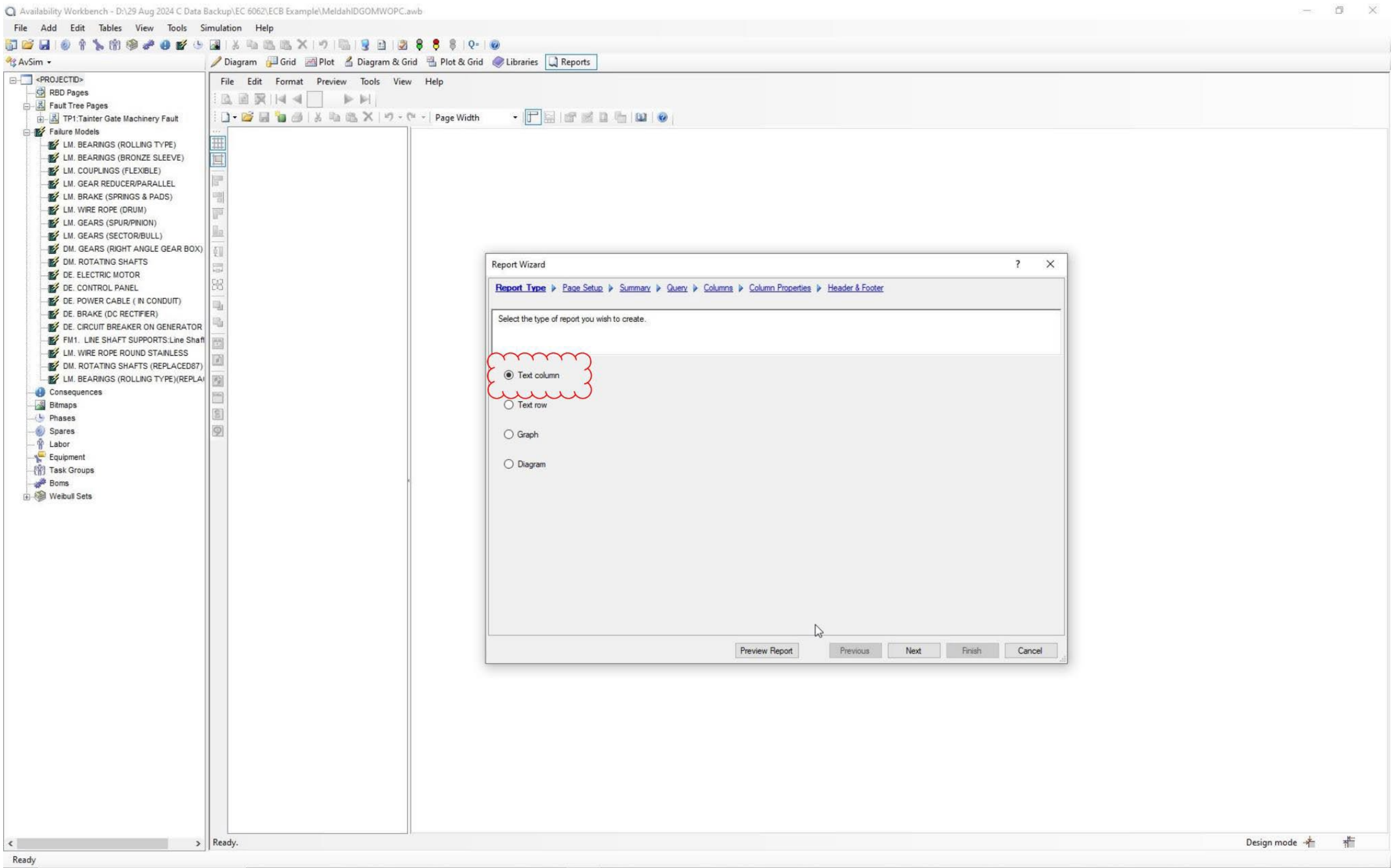

Use Shape Parameter of 4
Gamma or location parameter, represents the number years after project went into service that it was replaced, 0 if original
Use Non-operating Failure Apportionment of 15% for Wear, 20% for Fatigue, and 30% for Corrosion
Set Non-operating Aging Apportionment Factor at 100%
Characteristic Life from ERDC TR 13-4 Unless Not Available, Then Use FRM Data or Other Source
Failure Model Properties - DM. GEARS (RIGHT ANGLE GEAR BOX)
Left Side Drive Machinery
Wire Ropes

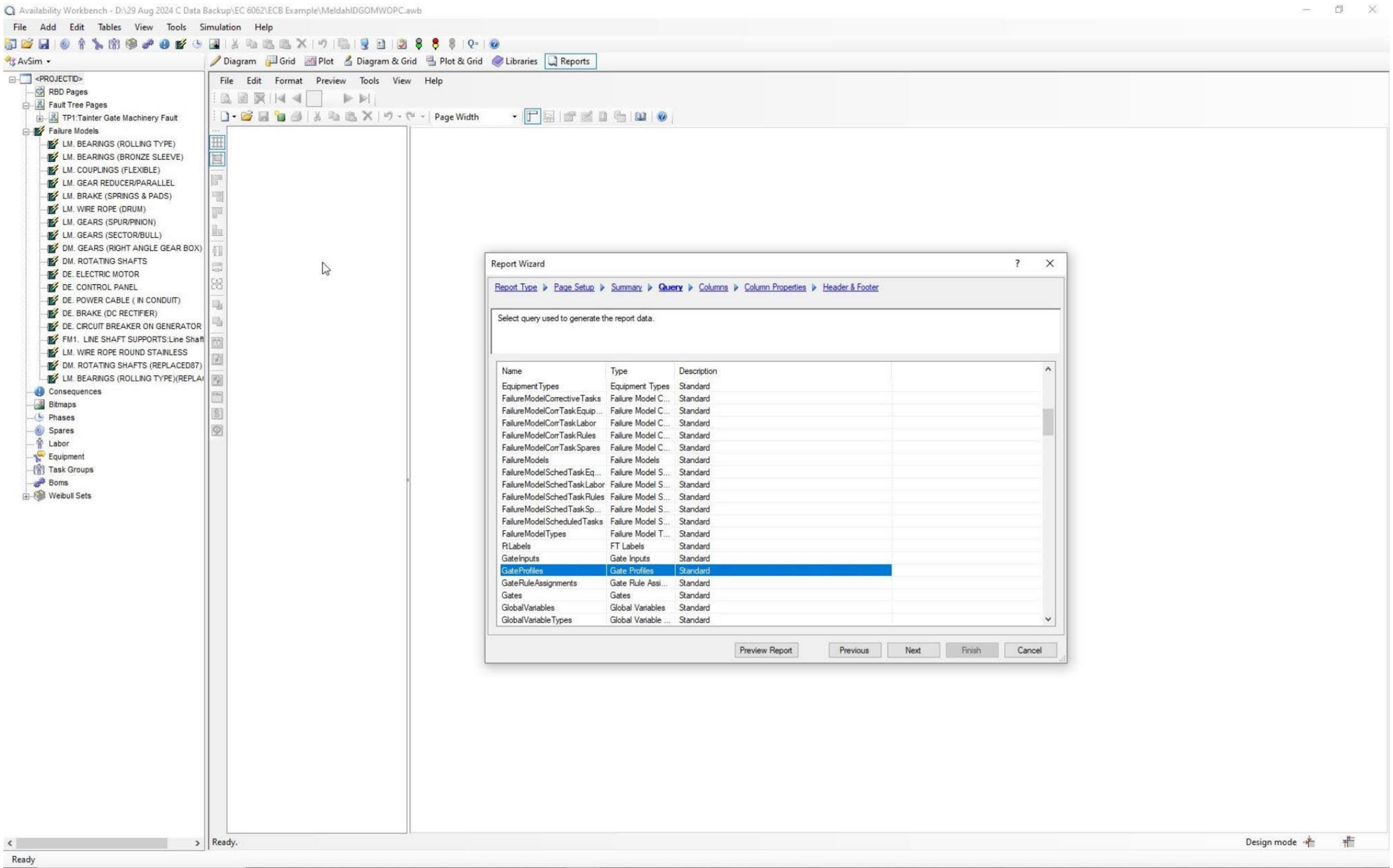

Left Side Drive Machinery
GT1
Parallel Shaft Reducer
High Speed Pinion
High Speed Gear
Drum Gear Pinion
Drum Gear
Wire Rope Drum
High Speed Pinion Shaft Bearing
Intermediate Shaft Bearing
Intermediate Shaft Bearing
Drum Shaft Bearing
Drum Shaft Bearing
Wire Rope and Connections
Intermediate Shaft
Drum Shaft
EV6
EV7
EV8
EV9
EV10
EV11
EV12
EV13
EV14
EV15
EV16
GT3
EV165
EV166
Wire Ropes
GT4
Primary Event Properties - EV6 : Parallel Shaft Reducer
Standby mode is Warm to represent that the machinery can still fail when not operating and allows use of non-operating apportionment factors
Load factor of 1 for typical USACE machinery, but can be higher for regular extreme loading or a history of issues

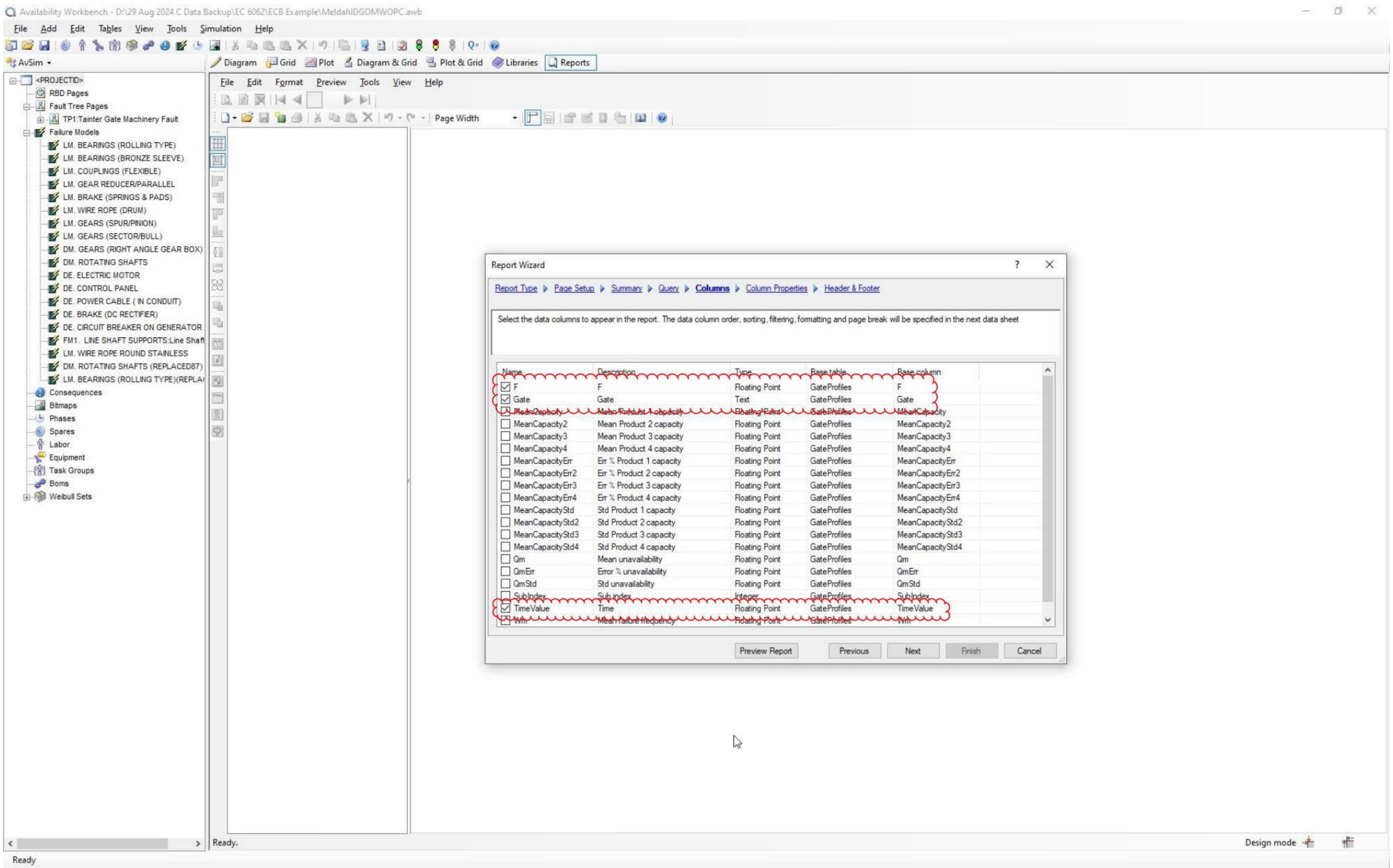

For Without Project Condition, lifetime should be set to age at project implementation plus 50 years
Set number of intervals to match the System Lifetime
Project Options
Lifetime: 114
Number of intervals: 114
Map to lifetime
Interval optimization
By cost
By availability
Apply inspection predictive data at time zero
OK
Cancel

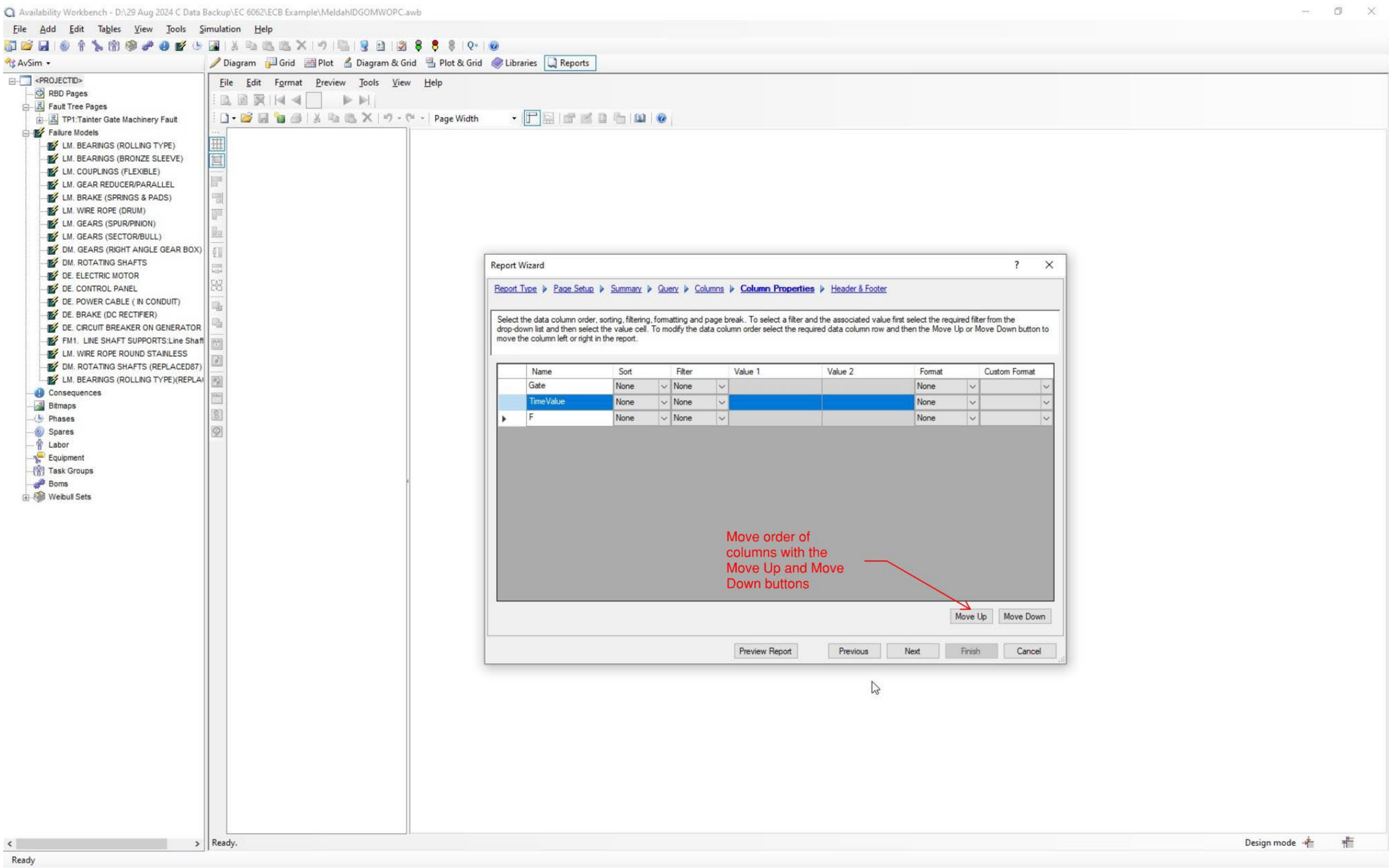

Sufficient simulations to converge in a reasonable amount of run time
Project Options
General
Lifetime
Simulation
Products
NPV
Spares
Importance
Capacity Availability
Number of simulations [1-1000000]:
50000
Random number seed:
Base buffer depletion rate on capacity requirement
Rules
ID
Description
Add...
Edit...
Move Up List
Move Down List
Remove
OK
Cancel
Wire Ropes
Wire Rope
EV17
EV116
EV117
EV118
EV119

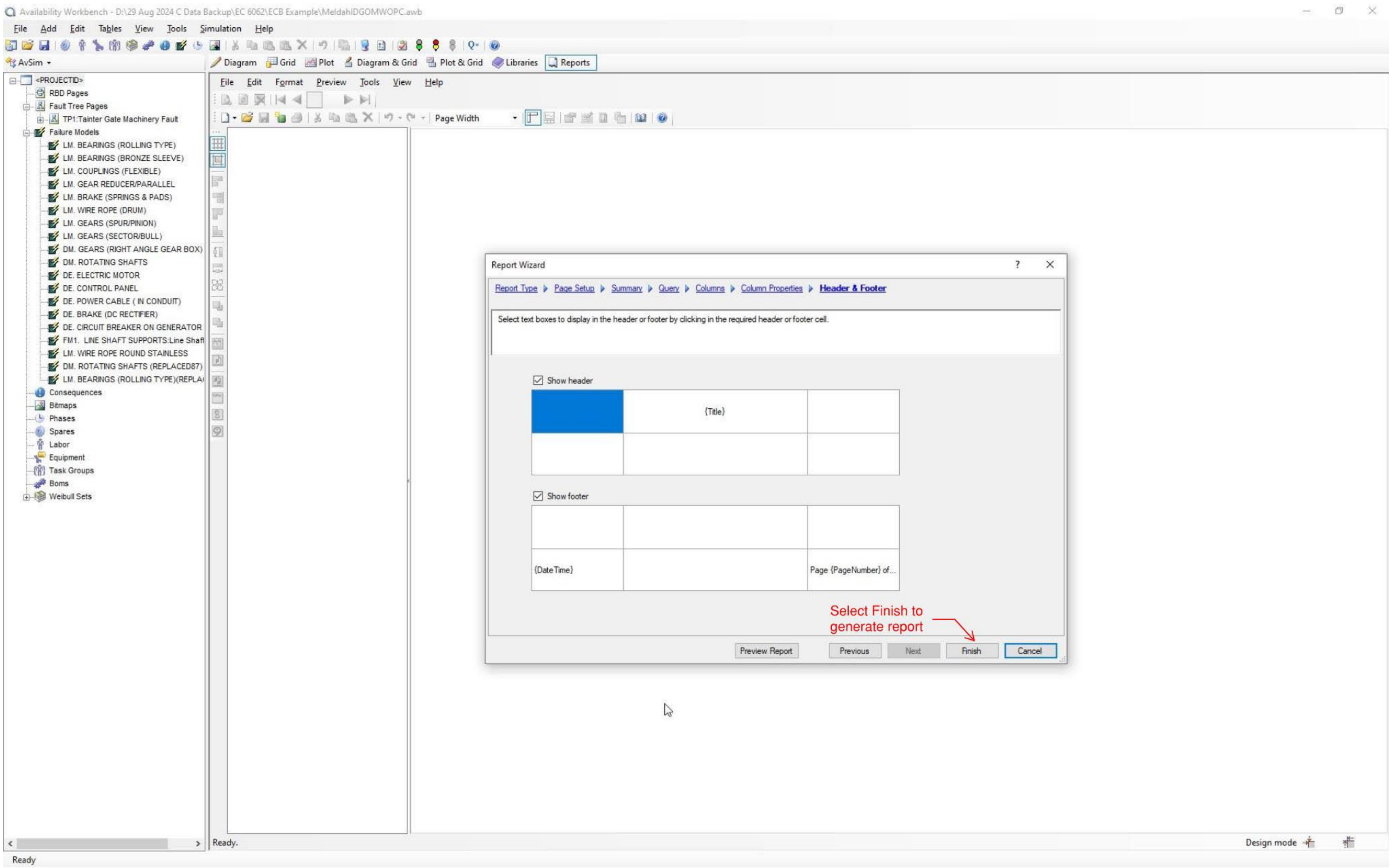

Availability Workbench - D:\29 Aug 2024 C Data Backup\EC 6062\ECB Example\MeldahlDGOMWOPC.awb
File Add Edit Tables View Tools Simulation Help
Diagram Grid Plot Diagram & Grid Plot & Grid Libraries Reports
1
File Edit Format Preview Tools View Help
New
Open Report... Ctrl+O
Design Report...
Report Wizard...
2
Close
Close All
Save Report Ctrl+S
Save Report As...
Save All Reports
Open Report Template...
Save Report As Template...
Publish Report in Word Format (docx)
Publish Report In Word Format (RTF)
Publish Report In PDF
Print Ctrl+P
Print Preview
Page Setup...
Export Data
Recent Reports
Page Width
RBD Pages
Fault Tree Pages
TP1:Tainter Gate Machinery Fault
Failure Models
LM. BEARINGS (ROLLING TYPE)
LM. BEARINGS (BRONZE SLEEVE)
LM. COUPLINGS (FLEXIBLE)
LM. GEAR REDUCER/PARALLEL
LM. BRAKE (SPRINGS & PADS)
LM. WIRE ROPE (DRUM)
LM. GEARS (SPUR/PINION)
LM. GEARS (SECTOR/BULL)
DM. GEARS (RIGHT ANGLE GEAR BOX)
DM. ROTATING SHAFTS
DE. ELECTRIC MOTOR
DE. CONTROL PANEL
DE. POWER CABLE (IN CONDUIT)
DE. BRAKE (DC RECTIFIER)
DE. CIRCUIT BREAKER ON GENERATOR
FM1. LINE SHAFT SUPPORTS:Line Shaft
LM. WIRE ROPE ROUND STAINLESS
DM. ROTATING SHAFTS (REPLACED87)
LM. BEARINGS (ROLLING TYPE)(REPLA
Consequences
Bitmaps
Phases
Spares
Labor
Equipment
Task Groups
Boms
Weibull Sets
Ready.
Design mode
Ready

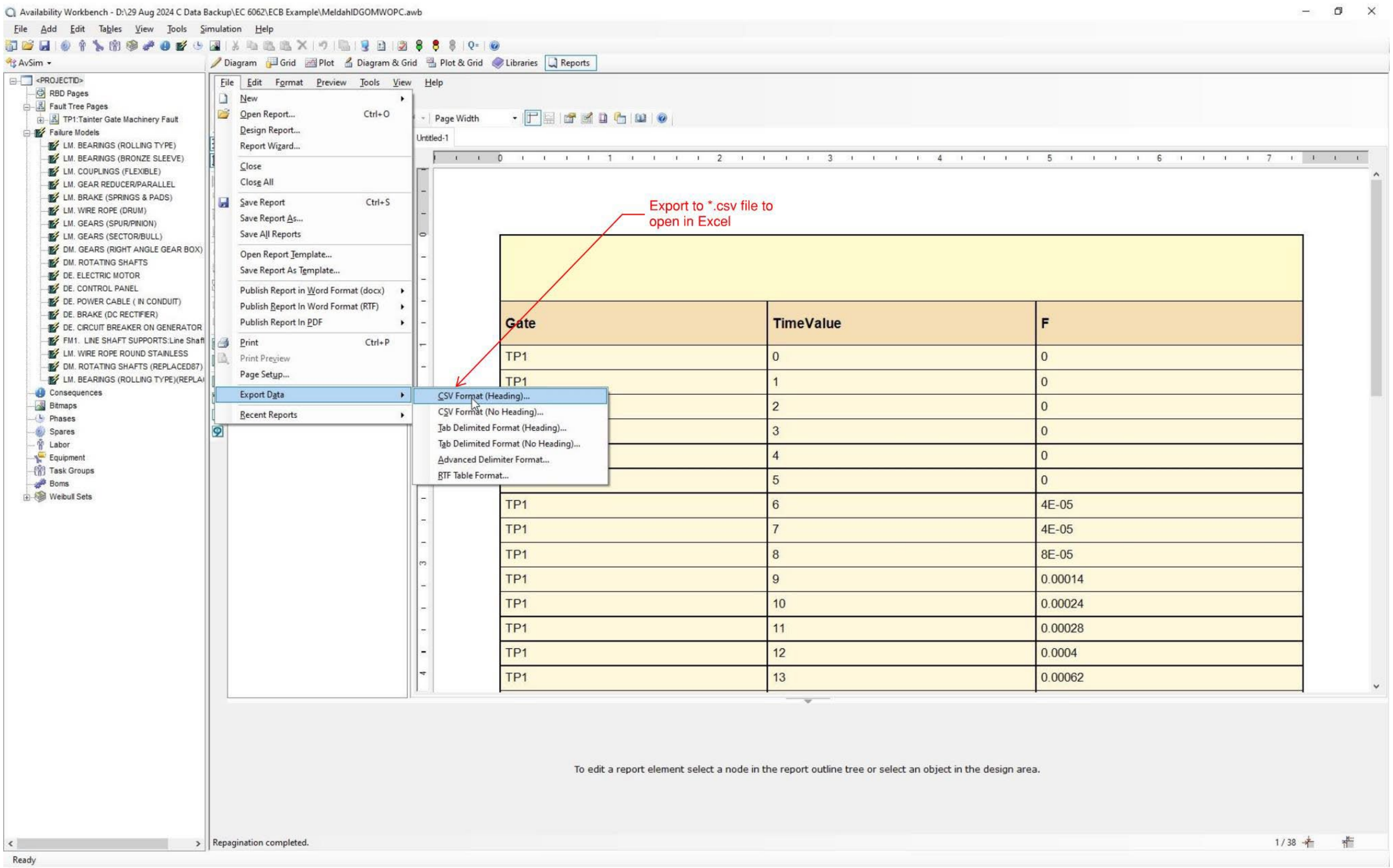

Report Wizard
Report Type
Page Setup
Summary
Query
Columns
Column Properties
Header & Footer
Select the type of report you wish to create.
Text column
Text row
Graph
Diagram
Preview Report
Previous
Next
Finish
Cancel






Report Wizard
Report Type
Page Setup
Summary
Query
Columns
Column Properties
Header & Footer
Select the data column order, sorting, filtering, formatting and page break. To select a filter and the associated value first select the required filter from the drop-down list and then select the value cell. To modify the data column order select the required data column row and then the Move Up or Move Down button to move the column left or right in the report.
Name
Sort
Filter
Value 1
Value 2
Format
Custom Format
Gate
TimeValue
F
Move order of columns with the Move Up and Move Down buttons
Move Up
Move Down
Preview Report
Previous
Next
Finish
Cancel

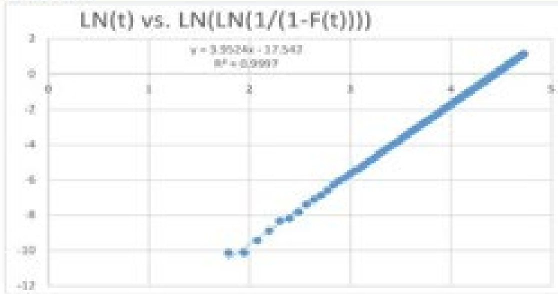

Report Wizard
Report Type ▶ Page Setup ▶ Summary ▶ Query ▶ Columns ▶ Column Properties ▶ Header & Footer
Select text boxes to display in the header or footer by clicking in the required header or footer cell.
Show header
{Title}
Show footer
{DateTime}
Page {PageNumber} of...
Select Finish to generate report
Preview Report
Previous
Next
Finish
Cancel


Export to *.csv file to open in Excel
Export Data
CSV Format (Heading)...
CSV Format (No Heading)...
Tab Delimited Format (Heading)...
Tab Delimited Format (No Heading)...
Advanced Delimiter Format...
RTF Table Format...
Gate
TimeValue
F
To edit a report element select a node in the report outline tree or select an object in the design area.
Repagination completed.

From exported "Time Value" and "F" or Unreliability for the top gate from AWB

Q - Q PLOT PARAMETER ESTIMATION USING AWB Outputs

Years of Service	"Unreliability" CDF	LN(t)	LN(LN(1/(1-F(t))))
6	4.00E-05	1.791759469	-10.1266111
7	4.00E-05	1.945910149	-10.1266111
8	0.00008	2.079441542	-9.433443922
9	0.00014	2.197224577	-8.873798131
10	0.00024	2.302585093	-8.334751623
11	0.00028	2.397895273	-8.180580938
12	0.0004	2.48490665	-7.823845978
13	0.00062	2.564949357	-7.385481
14	0.00082	2.63905733	-7.105796078
15	0.00104	2.708050201	-6.86801434
16	0.00136	2.772588722	-6.599590194
17	0.00184	2.833213344	-6.297069001
18	0.00236	2.890371758	-6.047912498
19	0.0028	2.944438979	-5.876734226
20	0.00344	2.995732274	-5.670561337
21	0.00418	3.044522438	-5.475350383
22	0.00464	3.091042453	-5.370716415
23	0.00576	3.135494216	-5.153930868
24	0.00684	3.17805383	-4.98153776
25	0.00786	3.218875825	-4.842025741
26	0.00924	3.258096538	-4.679575507
27	0.01098	3.295836866	-4.506164559
28	0.01286	3.33220451	-4.347168838
29	0.01462	3.36729583	-4.2180099
30	0.0166	3.401197382	-4.089994597
31	0.01894	3.433987204	-3.956933596
32	0.0209	3.465735903	-3.85746396
33	0.02368	3.496507561	-3.73116596
34	0.02724	3.526360525	-3.589291635
35	0.03048	3.555348061	-3.475247384
36	0.03432	3.583518938	-3.354616439
37	0.03798	3.610917913	-3.251398022
38	0.0419	3.63758616	-3.151144228
39	0.0463	3.663561646	-3.049003894
40	0.05108	3.688879454	-2.948261395
41	0.05602	3.713572067	-2.853359837
42	0.06136	3.737669618	-2.759502563
43	0.06718	3.761200116	-2.665809685
44	0.07296	3.784189634	-2.58020378
45	0.079	3.80666249	-2.497441977
46	0.0856	3.828641396	-2.413660055
47	0.09324	3.850147602	-2.324038863
48	0.10094	3.871201011	-2.240497956
49	0.10852	3.891820298	-2.163934411
50	0.11754	3.912023005	-2.079107062
51	0.1271	3.931825633	-1.995583766
52	0.13634	3.951243719	-1.92021049
53	0.14614	3.970291914	-1.845235989
54	0.15666	3.988984047	-1.769694222
55	0.16714	4.007333185	-1.698871941
56	0.17818	4.025351691	-1.628448035
57	0.18956	4.043051268	-1.559800636
58	0.20146	4.060443011	-1.491787247
59	0.2143	4.077537444	-1.422210746
60	0.22658	4.094344562	-1.358939772
61	0.23856	4.110873864	-1.299955571
62	0.25244	4.127134385	-1.23463578
63	0.26654	4.143134726	-1.171240351
64	0.28106	4.158883083	-1.108731191
65	0.2966	4.17438727	-1.044608428
66	0.31208	4.189654742	-0.983278311
67	0.32638	4.204692619	-0.928643906
68	0.34258	4.219507705	-0.868853398
69	0.35832	4.234106505	-0.812684284
70	0.3746	4.248495242	-0.756377046
71	0.3914	4.262679877	-0.699982405
72	0.40936	4.276666119	-0.641411674
73	0.42658	4.290459441	-0.586740888
74	0.4447	4.304065093	-0.530608741
75	0.4613	4.317488114	-0.480302159
76	0.47912	4.33073334	-0.427349448



Parameter estimation via ordinary least square using Weibull plot with trendline using linear best-fit regression.
AKA - Median Rank Regression Estimation

X-Axis Intercept	-17.5415
Slope of Line	3.952384

Weibull shape parameter or Beta

2-Parameter Weibull		
Shape parameter	3.95	**= Slope of Line**
Scale parameter	84.62	**=e ^ -(intercept/shape)**

Characteristic life or Alpha

The CDF of a Weibull Distribution is given as:

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

Here, the CDF is a function of time, t. The two Weibull parameters represented are the scale parameter, α, and the shape parameter, β. Linearizing this distribution, yields the linear form of the CDF:

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

Here, it can be observed that this takes the slope intercept form of a linear equation, y = mx+b, where:

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

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

$$x = \ln(t)$$

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

b, the intercept of the line is given by:

$$b = \beta\ln(\alpha)$$

α is found by its relationship to β and the y intercept of the line:

77	0.49662	4.343805422	-0.376280269
78	0.51404	4.356708827	-0.326244174
79	0.53164	4.369447852	-0.276388686
80	0.54894	4.382026635	-0.227961501
81	0.56692	4.394449155	-0.178130977
82	0.58468	4.406719247	-0.129304941
83	0.6015	4.418840608	-0.083329675
84	0.61888	4.430816799	-0.035999275
85	0.63668	4.442651256	0.012394164
86	0.65304	4.454347296	0.05689606
87	0.66976	4.465908119	0.102498478
88	0.6863	4.477336814	0.147832042
89	0.70246	4.48863637	0.192442343
90	0.71822	4.49980967	0.236358768
91	0.7337	4.510859507	0.280001492
92	0.75014	4.521788577	0.327038246
93	0.76406	4.532599493	0.367540124
94	0.77794	4.543294782	0.408665092
95	0.79274	4.553876892	0.453481154
96	0.8065	4.564348191	0.496205935
97	0.81888	4.574710979	0.535671679
98	0.83206	4.584967479	0.578941274
99	0.84398	4.59511985	0.619377422
100	0.85532	4.605170186	0.65919263
101	0.86586	4.615120517	0.697572996
102	0.8761	4.624972813	0.736340995
103	0.88708	4.634728988	0.779818184
104	0.89638	4.644390899	0.818468363
105	0.90552	4.65396035	0.858393408
106	0.9137	4.663439094	0.89605769
107	0.92114	4.672828834	0.93219603
108	0.9283	4.682131227	0.968983568
109	0.9352	4.691347882	1.006661341
110	0.94184	4.700480366	1.0454075
111	0.94702	4.709530201	1.077674888
112	0.95208	4.718498871	1.111272583
113	0.95692	4.727387819	1.14571736