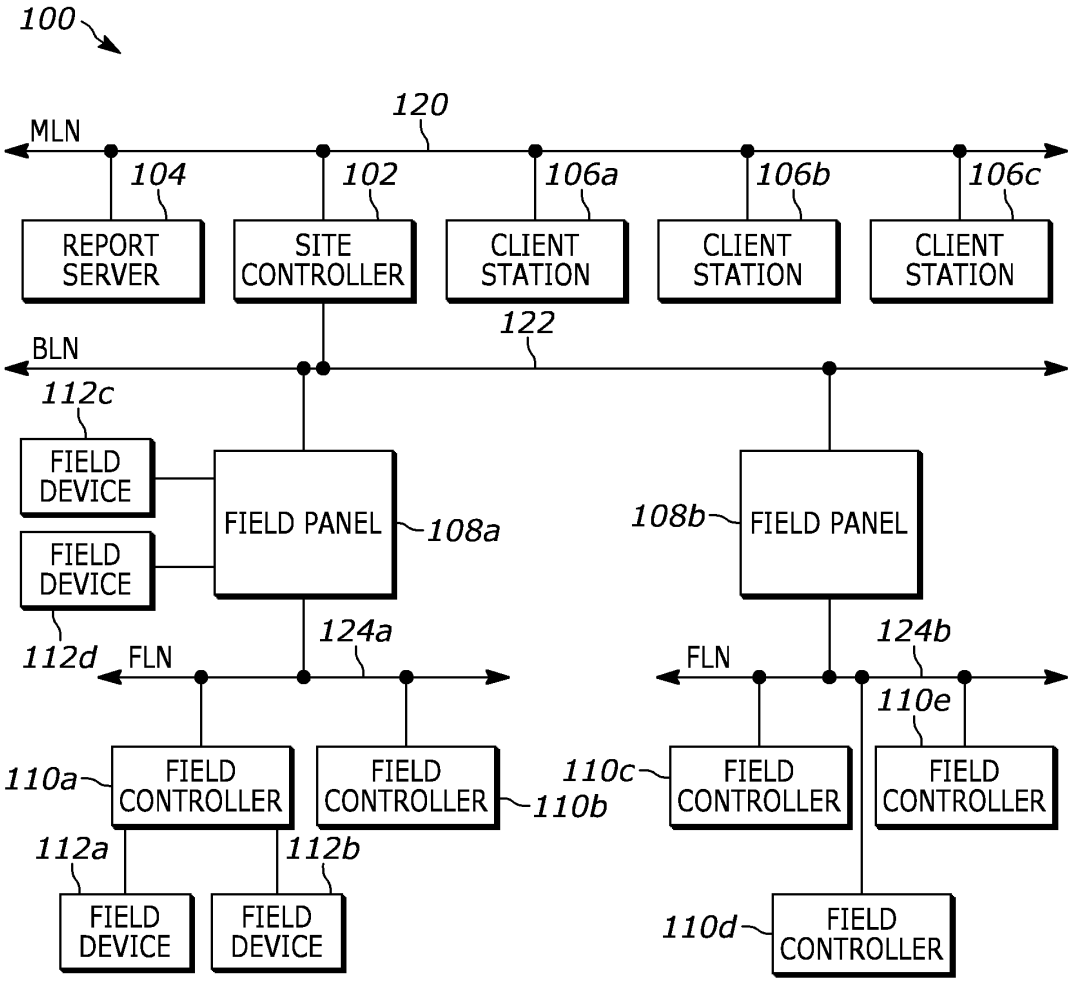
100
120
MLN
104
102
106a
106b
106c
REPORT SERVER
SITE CONTROLLER
CLIENT STATION
CLIENT STATION
CLIENT STATION
122
BLN
112c
FIELD DEVICE
FIELD DEVICE
FIELD PANEL
108a
108b
FIELD PANEL
112d
FLN
124a
FLN
124b
110e
110a
FIELD CONTROLLER
FIELD CONTROLLER
110b
110c
FIELD CONTROLLER
FIELD CONTROLLER
112a
112b
FIELD DEVICE
FIELD DEVICE
110d
FIELD CONTROLLER

FIG. 1

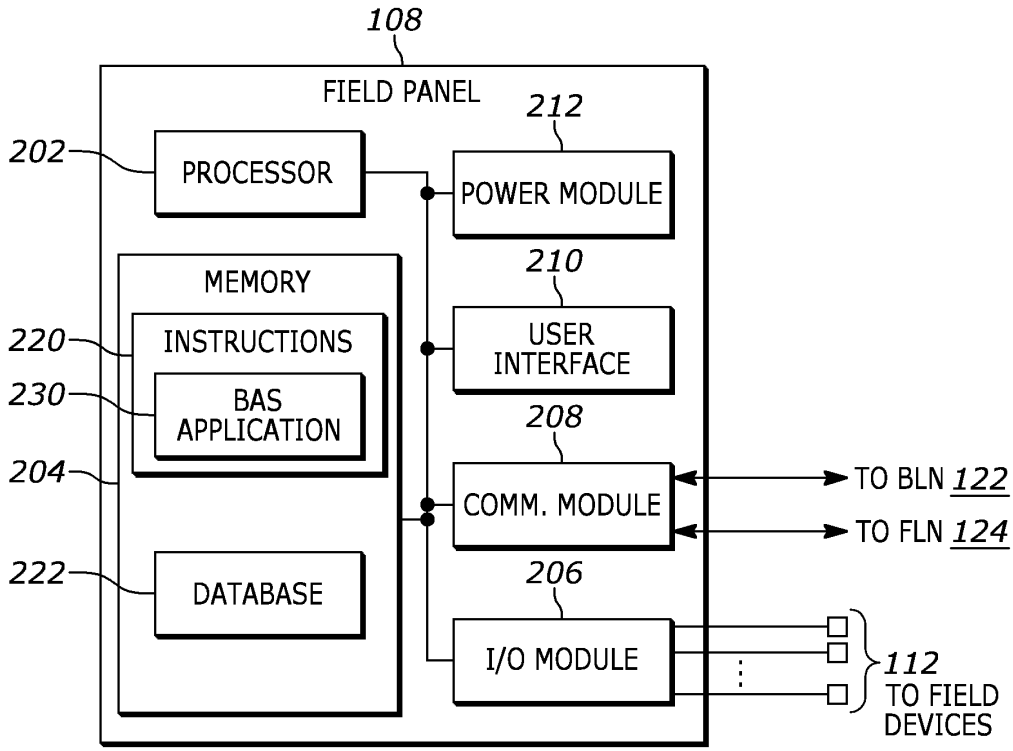
108
FIELD PANEL
212
202
PROCESSOR
POWER MODULE
210
MEMORY
220
INSTRUCTIONS
USER INTERFACE
230
BAS APPLICATION
208
204
COMM. MODULE
TO BLN 122
TO FLN 124
222
DATABASE
206
I/O MODULE
112
TO FIELD DEVICES

FIG. 2

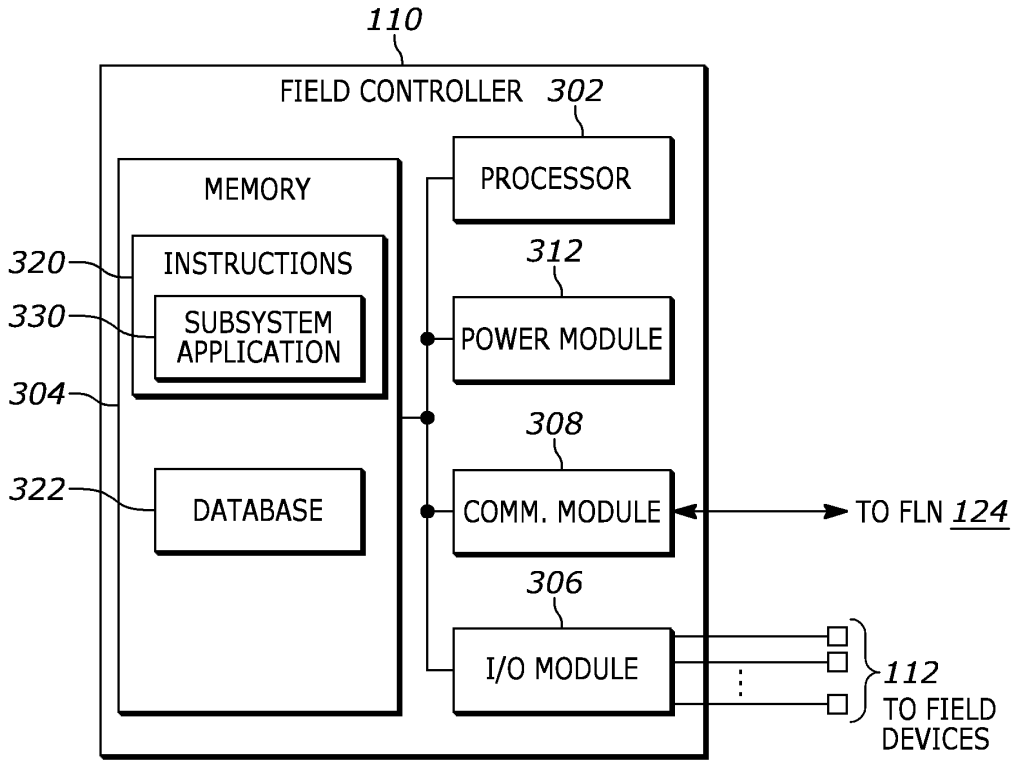
110
FIELD CONTROLLER 302
PROCESSOR
MEMORY
312
320
INSTRUCTIONS
POWER MODULE
330
SUBSYSTEM APPLICATION
304
308
322
DATABASE
COMM. MODULE
TO FLN 124
306
I/O MODULE
112
TO FIELD DEVICES

FIG. 3

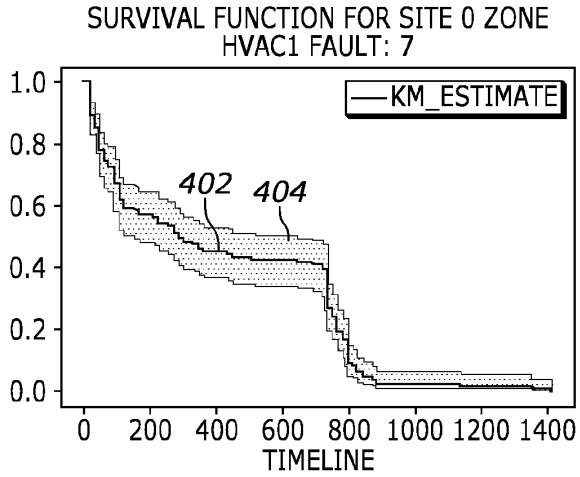

FIG. 4A

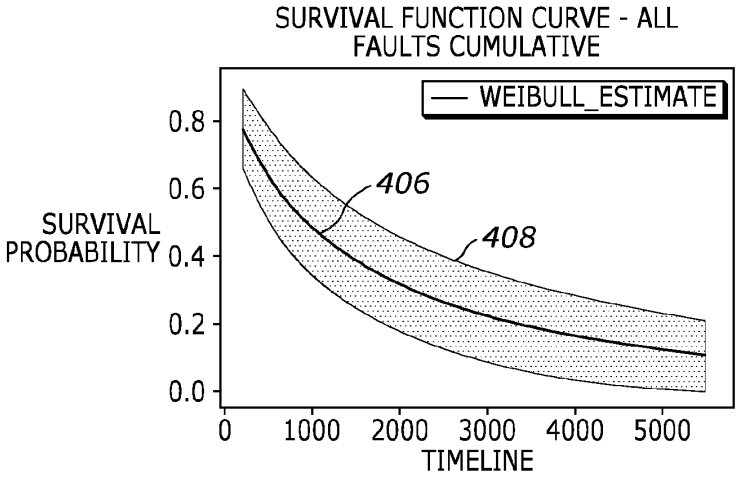

FIG. 4B

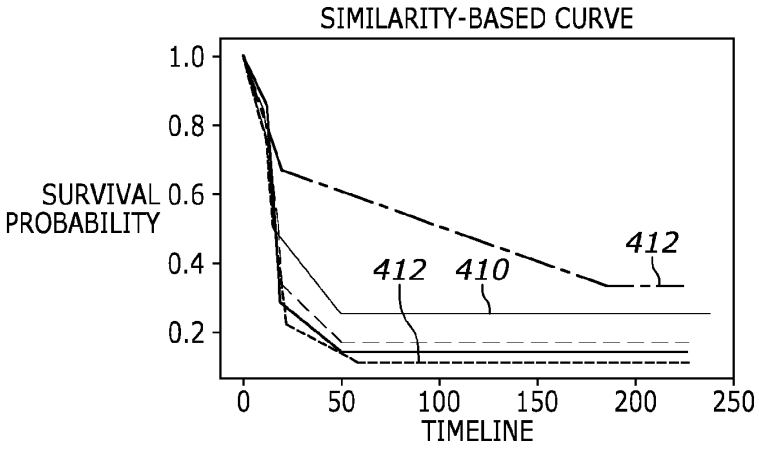

FIG. 4C

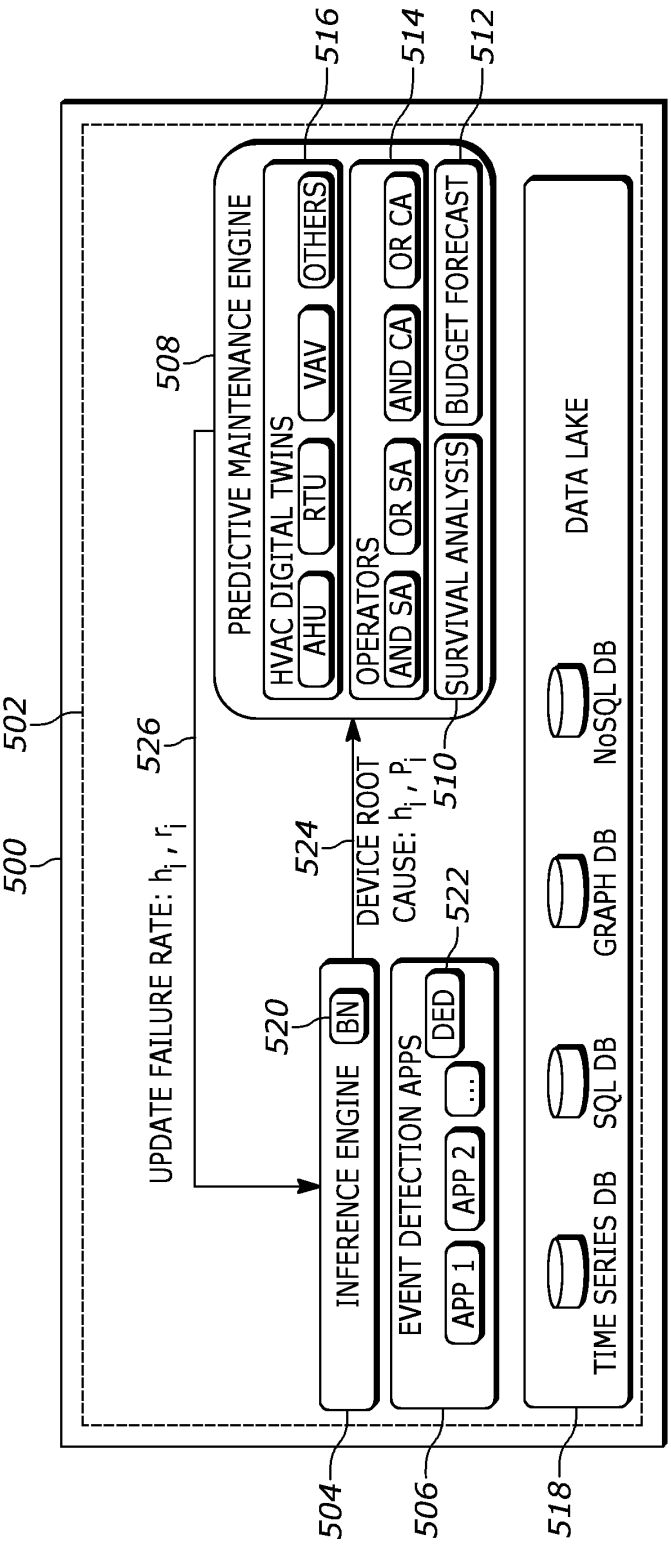
500
502
504
506
508
510
512
514
516
518
520
522
524
526
PREDICTIVE MAINTENANCE ENGINE
HVAC DIGITAL TWINS
AHU
RTU
VAV
OTHERS
OPERATORS
AND SA
OR SA
AND CA
OR CA
SURVIVAL ANALYSIS
BUDGET FORECAST
DATA LAKE
NoSQL DB
GRAPH DB
SQL DB
TIME SERIES DB
INFERENCE ENGINE
BN
EVENT DETECTION APPS
APP 1
APP 2
...
DED
UPDATE FAILURE RATE: h_i , r_i
DEVICE ROOT CAUSE: h_i , P_i

FIG. 5

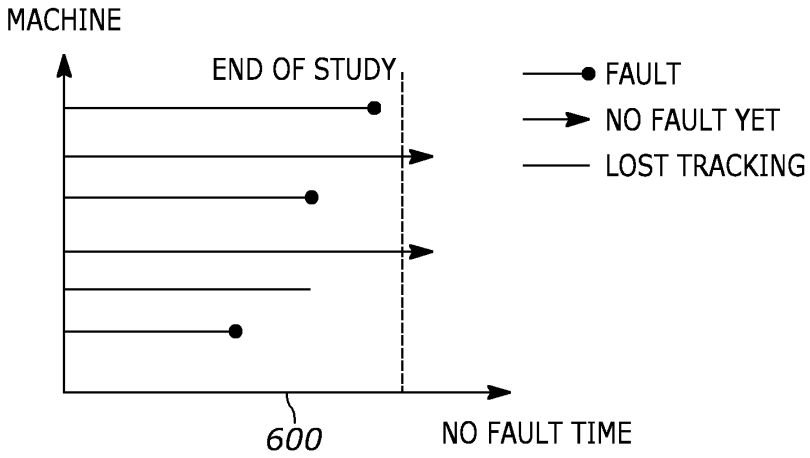
MACHINE
END OF STUDY
FAULT
NO FAULT YET
LOST TRACKING
600
NO FAULT TIME

FIG. 6

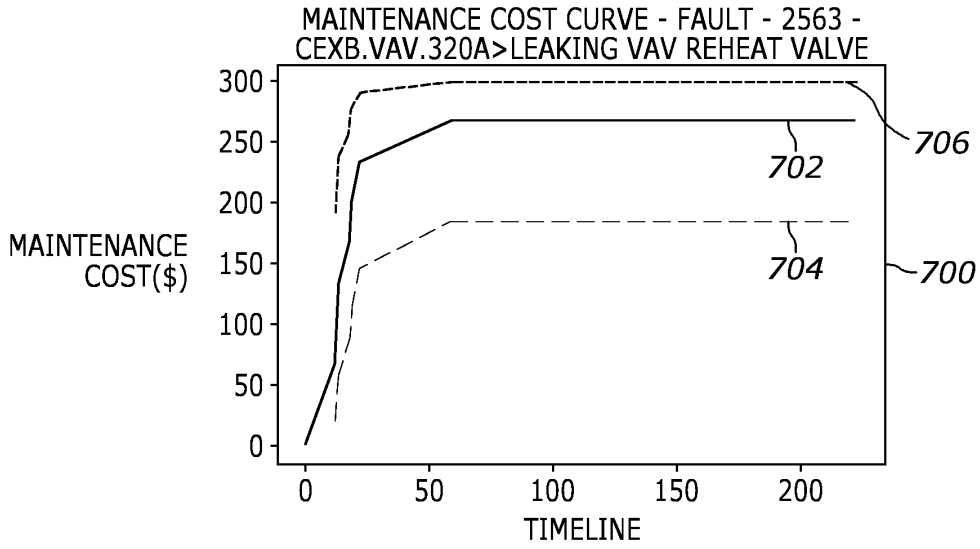
MAINTENANCE COST CURVE - FAULT - 2563 - CEXB.VAV.320A>LEAKING VAV REHEAT VALVE
MAINTENANCE COST($)
300
250
200
150
100
50
0
0
50
100
150
200
TIMELINE
706
702
704
700

FIG. 7

800

TIME	DEVICE	SITE	EVENT	PROBABILITY	MANUAL
10/1/2019 9:01	VALVE 1	BUILDING 1	FAULT	92	NO
10/1/2019 10:30	VALVE 1	BUILDING 1	FAULT VERIFIED AND VALVE REPLACED	100	YES
10/2/2019 11:20	VALVE 2	BUILDING 2	FAULT	72	NO

FIG. 8

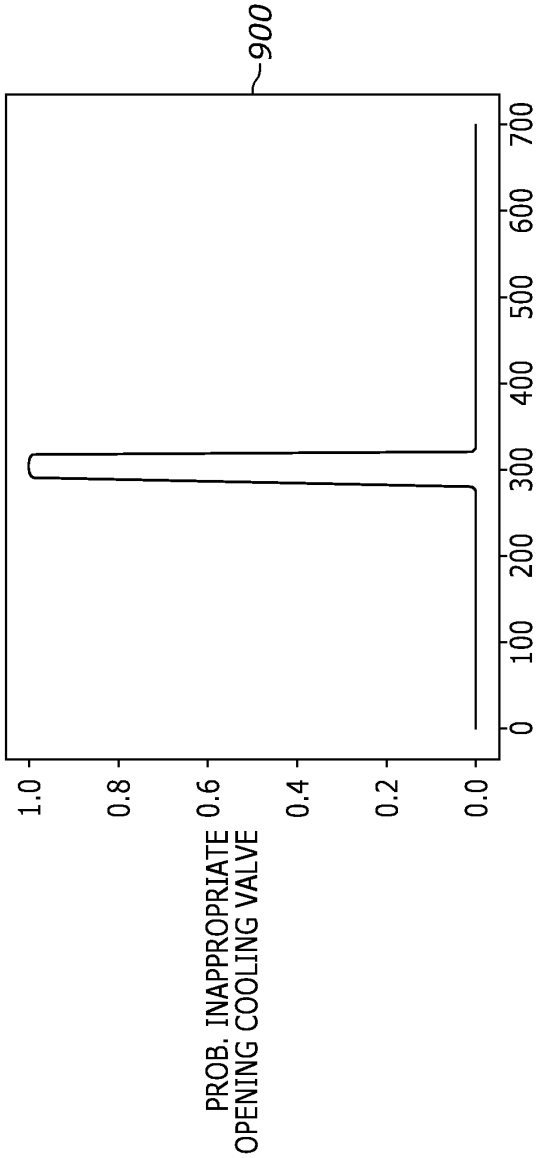

FIG. 9

1000

TIME	PROBABILITY OF FAILURE
1.00	0.2
1.01	0.3
1.07	0.4
1.10	0.9

FIG. 10

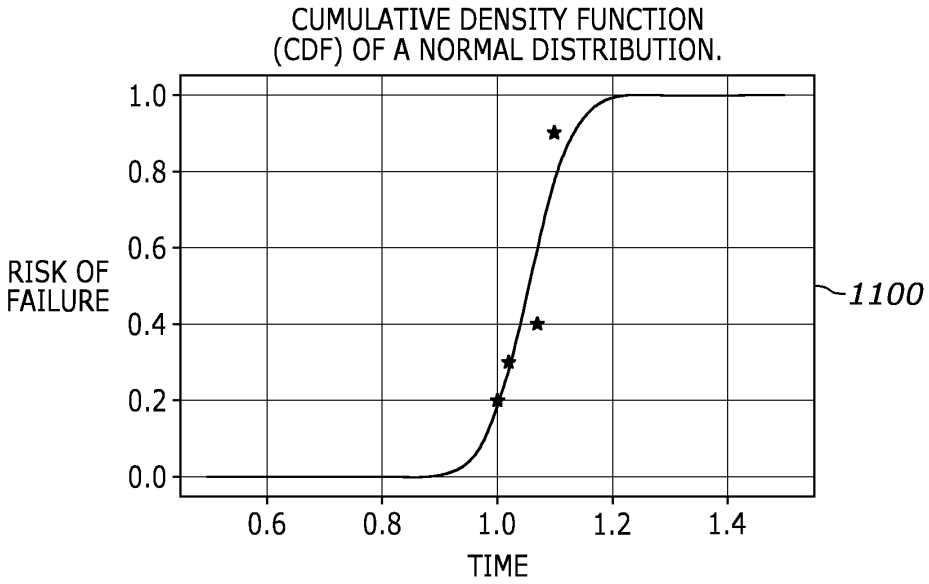

FIG. 11

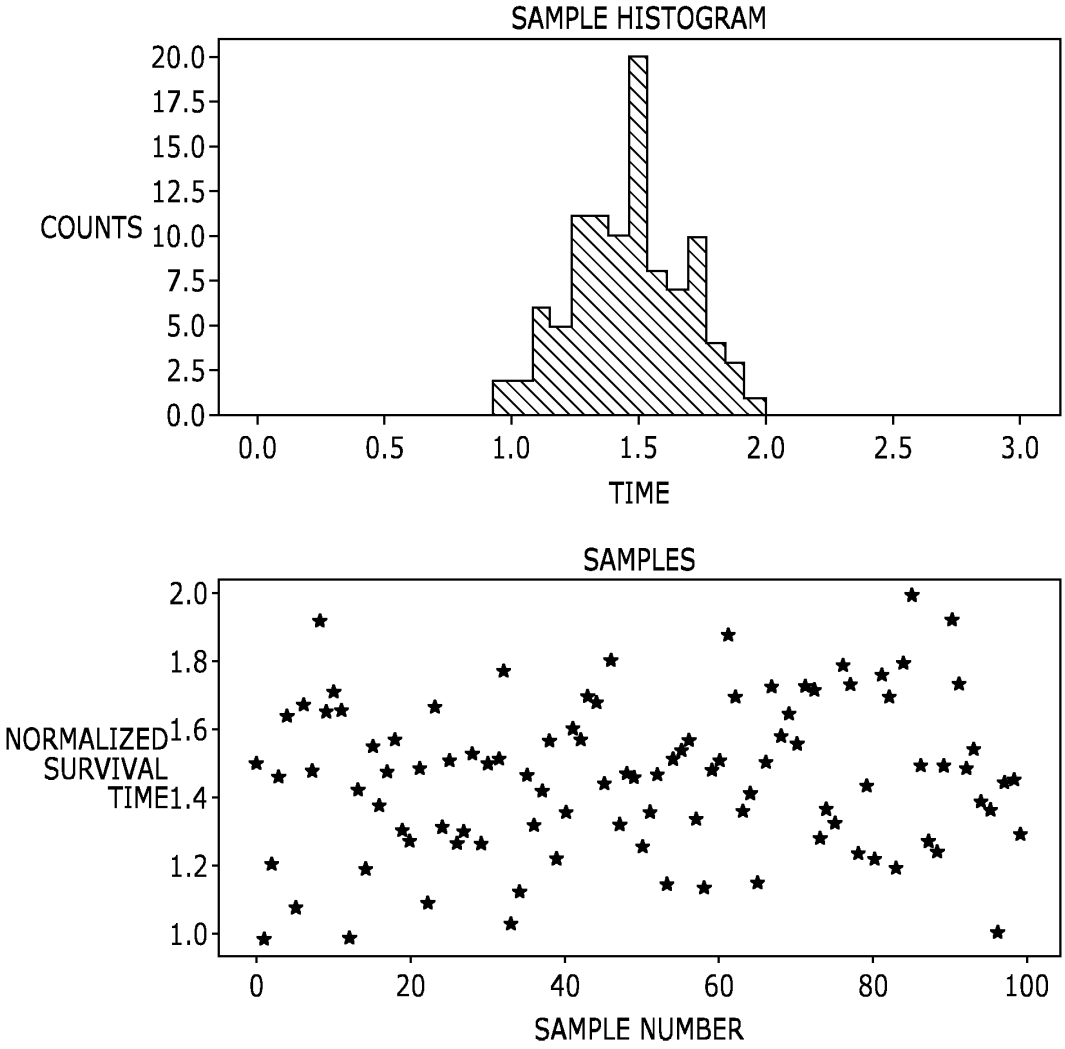

FIG. 12

1300

NORMALIZED TIME	PROBABILITY
1.49723115	1
0.98537847	1
1.20183954	1
1.45784079	1
1.64012221	1
...	

FIG. 13

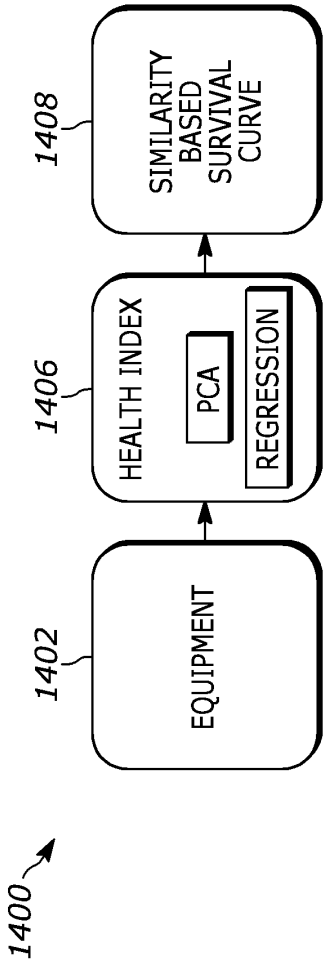

FIG. 14A

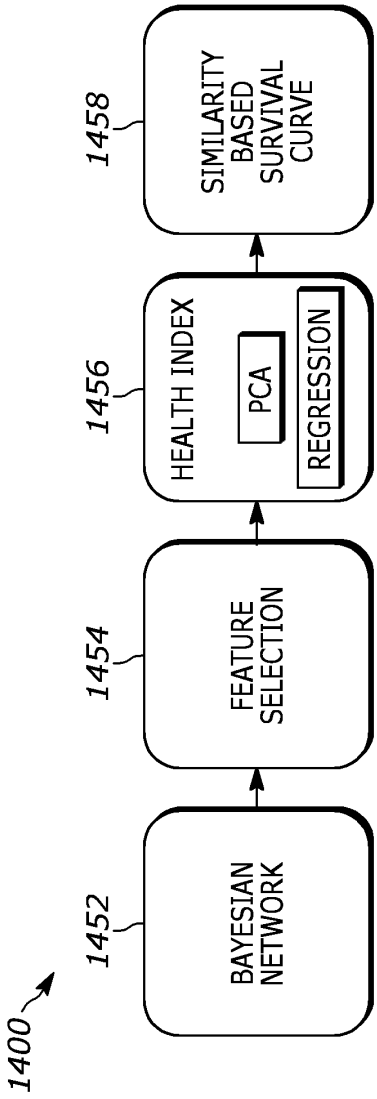

FIG. 14B

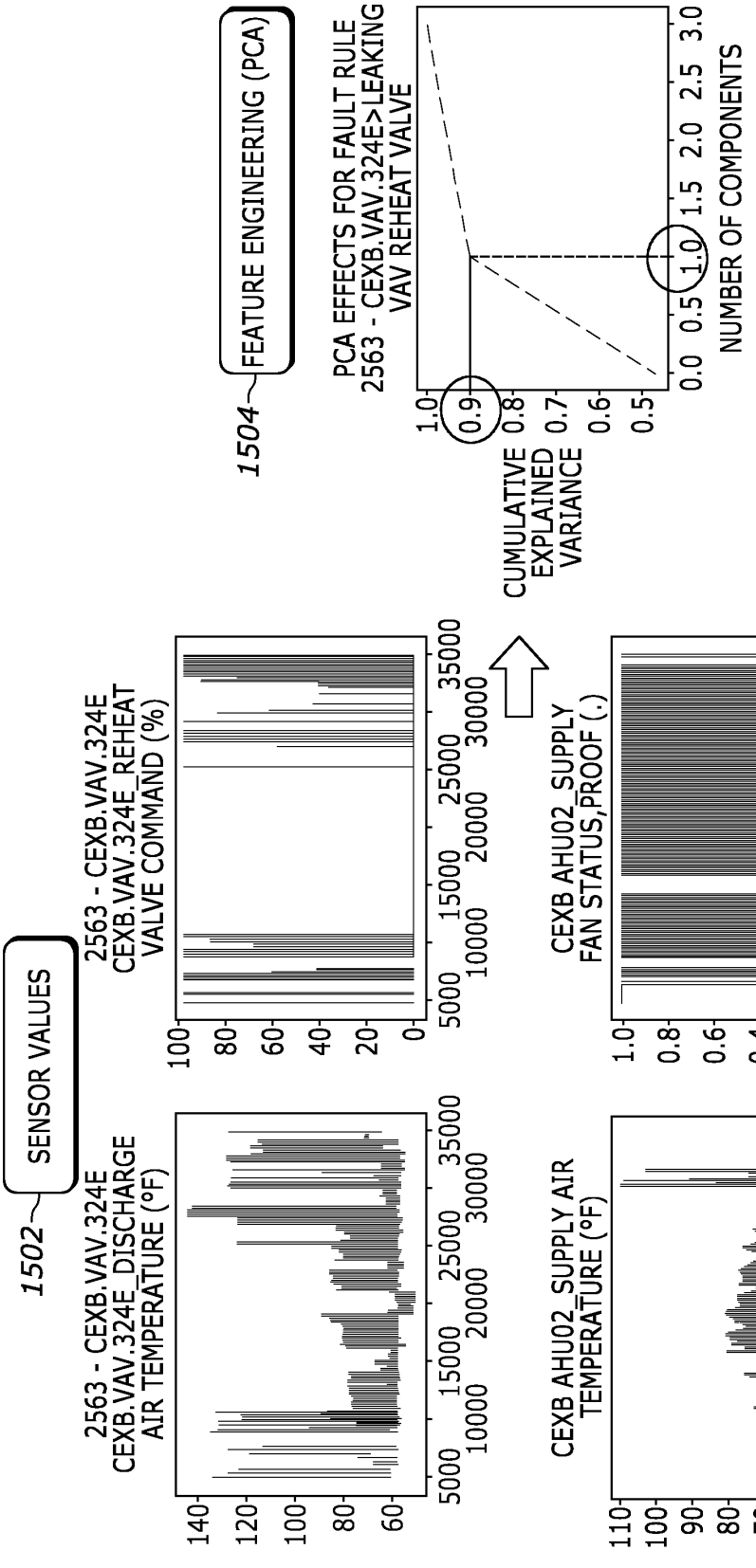
1502
SENSOR VALUES
2563 - CEXB.VAV.324E
CEXB.VAV.324E_DISCHARGE
AIR TEMPERATURE (°F)
2563 - CEXB.VAV.324E
CEXB.VAV.324E_REHEAT
VALVE COMMAND (%)
CEXB AHU02_SUPPLY AIR
TEMPERATURE (°F)
CEXB AHU02_SUPPLY
FAN STATUS,PROOF (.)
1504
FEATURE ENGINEERING (PCA)
PCA EFFECTS FOR FAULT RULE
2563 - CEXB.VAV.324E>LEAKING
VAV REHEAT VALVE
CUMULATIVE
EXPLAINED
VARIANCE
NUMBER OF COMPONENTS

FIG. 15A

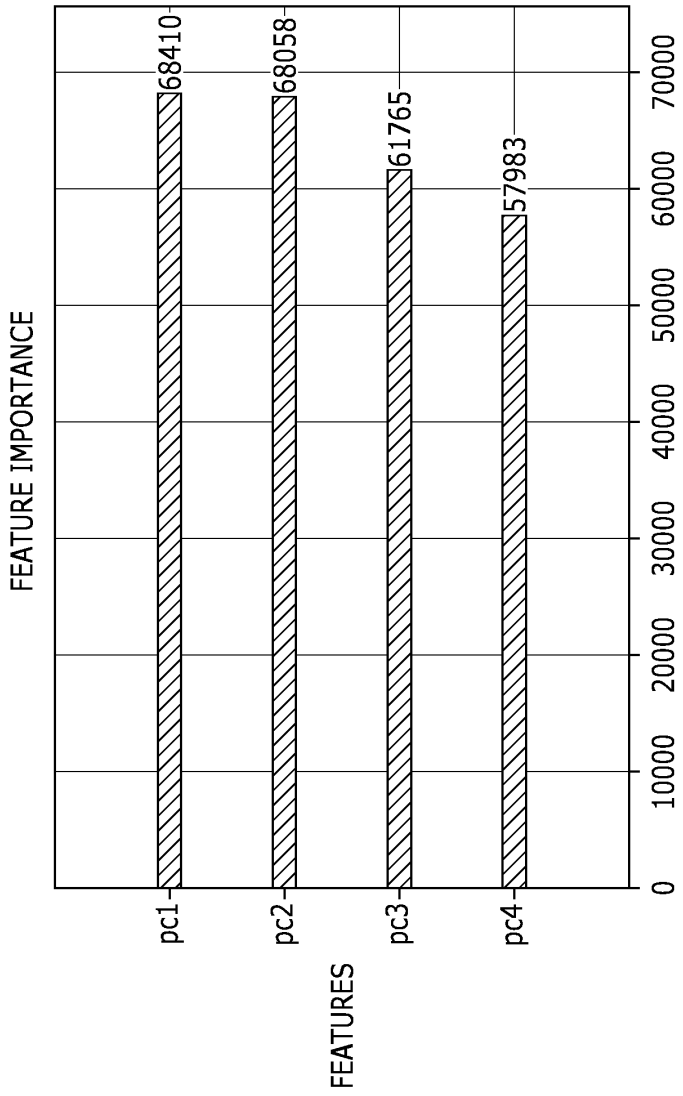
FEATURE IMPORTANCE
68410
68058
61765
57983
pc1
pc2
pc3
pc4
FEATURES
0
10000
20000
30000
40000
50000
60000
70000
F SCORE

FIG. 15B

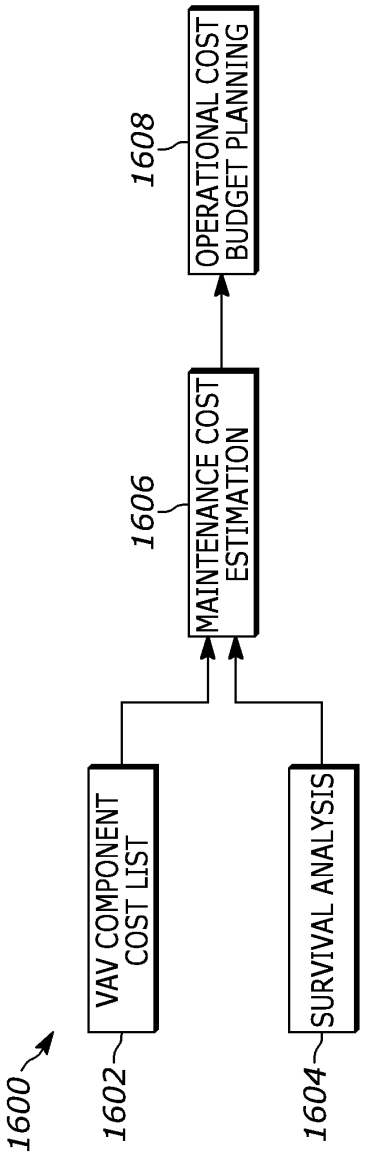

FIG. 16

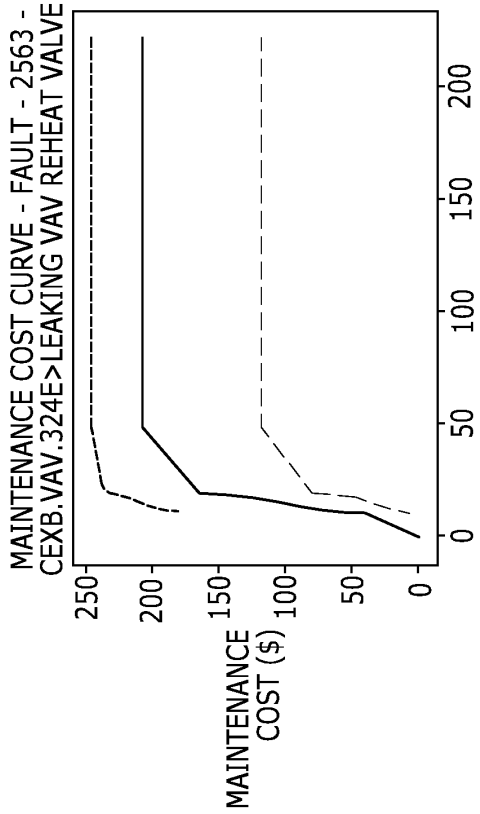

FIG. 17B

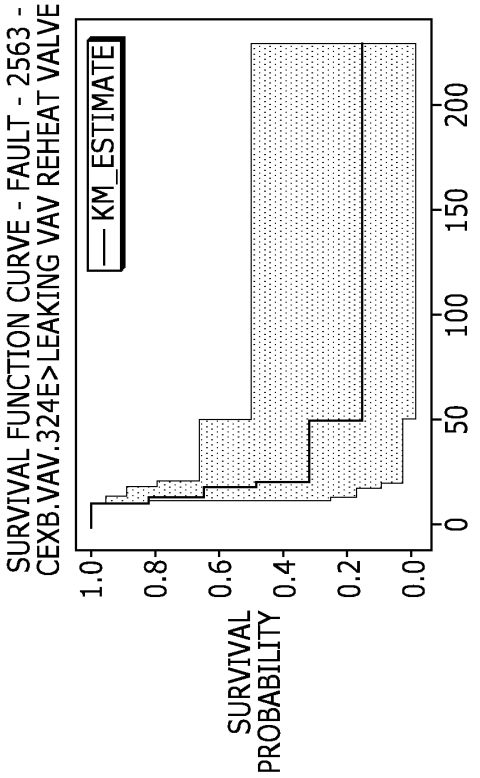

FIG. 17A

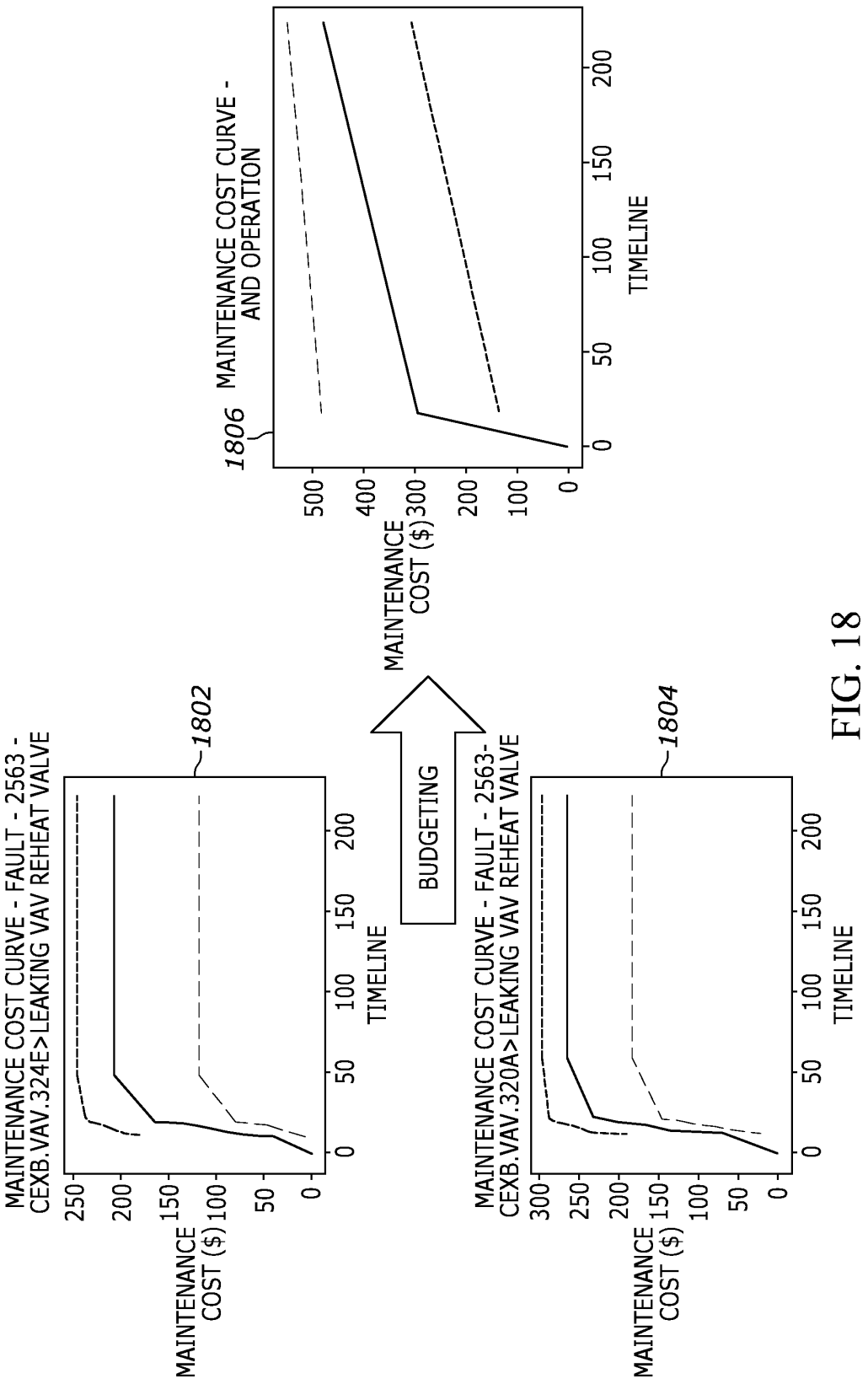
MAINTENANCE COST CURVE - FAULT - 2563 - CEXB.VAV.324E>LEAKING VAV REHEAT VALVE
1802
MAINTENANCE COST ($)
TIMELINE
BUDGETING
MAINTENANCE COST CURVE - AND OPERATION
1806
MAINTENANCE COST ($)
TIMELINE
MAINTENANCE COST CURVE - FAULT - 2563- CEXB.VAV.320A>LEAKING VAV REHEAT VALVE
1804
MAINTENANCE COST ($)
TIMELINE

FIG. 18

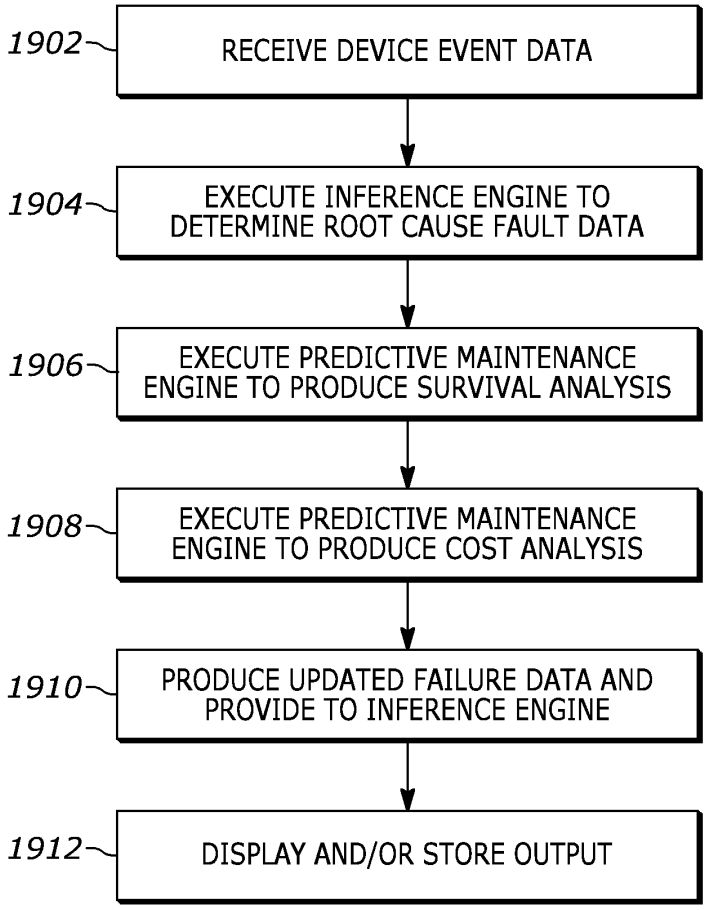
1902
RECEIVE DEVICE EVENT DATA
1904
EXECUTE INFERENCE ENGINE TO DETERMINE ROOT CAUSE FAULT DATA
1906
EXECUTE PREDICTIVE MAINTENANCE ENGINE TO PRODUCE SURVIVAL ANALYSIS
1908
EXECUTE PREDICTIVE MAINTENANCE ENGINE TO PRODUCE COST ANALYSIS
1910
PRODUCE UPDATED FAILURE DATA AND PROVIDE TO INFERENCE ENGINE
1912
DISPLAY AND/OR STORE OUTPUT

FIG. 19

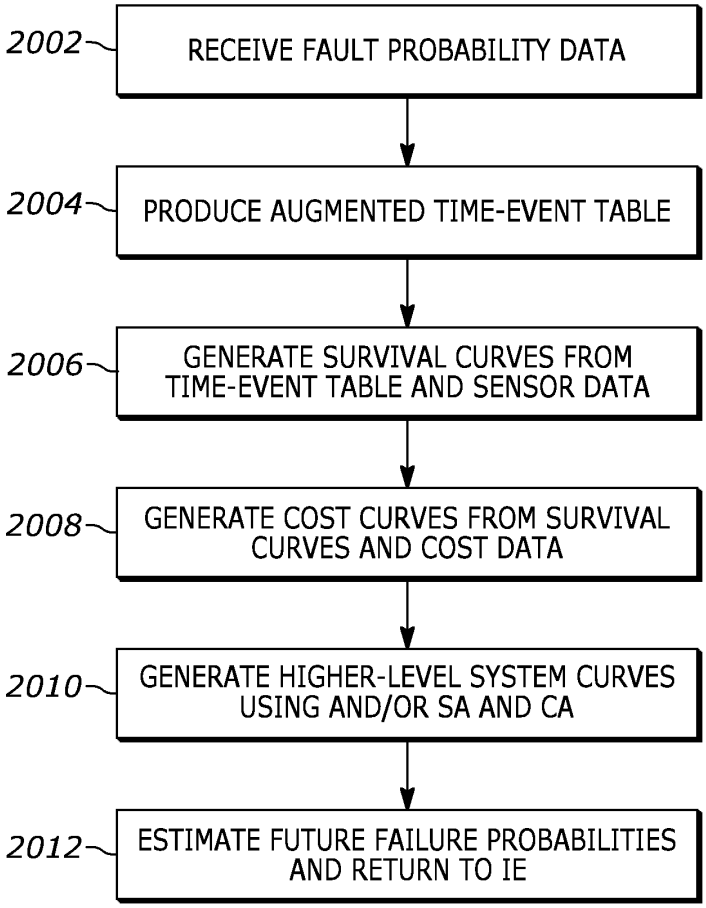
2002
RECEIVE FAULT PROBABILITY DATA
2004
PRODUCE AUGMENTED TIME-EVENT TABLE
2006
GENERATE SURVIVAL CURVES FROM TIME-EVENT TABLE AND SENSOR DATA
2008
GENERATE COST CURVES FROM SURVIVAL CURVES AND COST DATA
2010
GENERATE HIGHER-LEVEL SYSTEM CURVES USING AND/OR SA AND CA
2012
ESTIMATE FUTURE FAILURE PROBABILITIES AND RETURN TO IE

FIG. 20

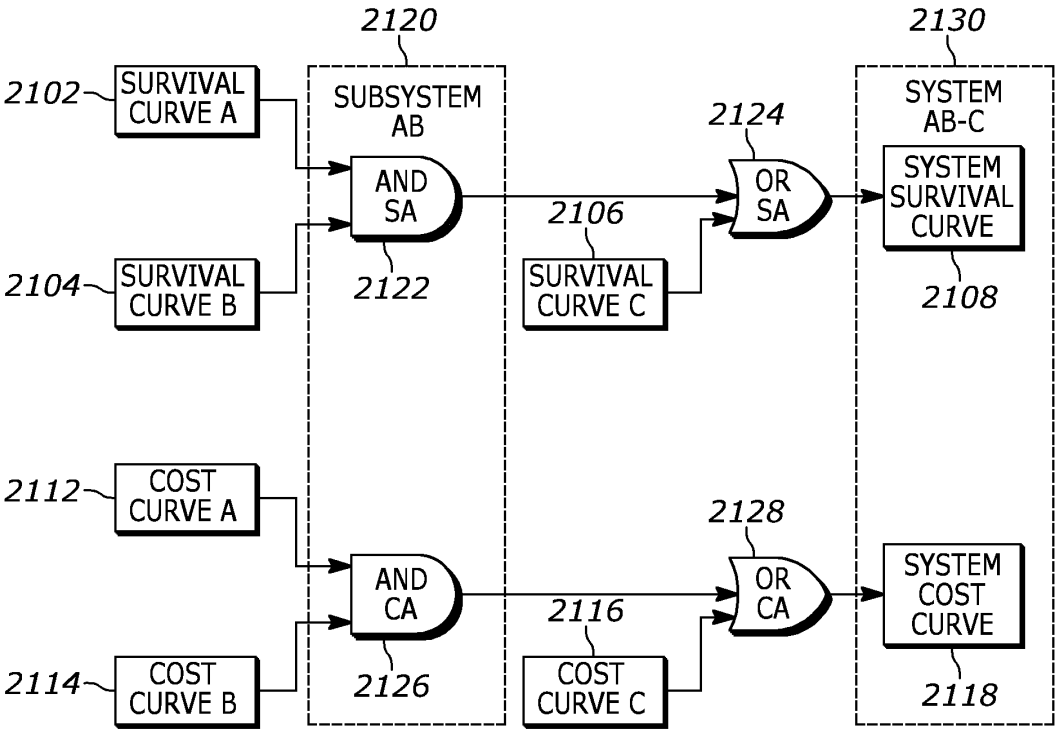
2120
2130
2102
SURVIVAL CURVE A
SUBSYSTEM AB
SYSTEM AB-C
2124
AND SA
OR SA
SYSTEM SURVIVAL CURVE
2106
2104
SURVIVAL CURVE B
2122
SURVIVAL CURVE C
2108
2112
COST CURVE A
2128
AND CA
OR CA
SYSTEM COST CURVE
2116
2114
COST CURVE B
2126
COST CURVE C
2118

FIG. 21

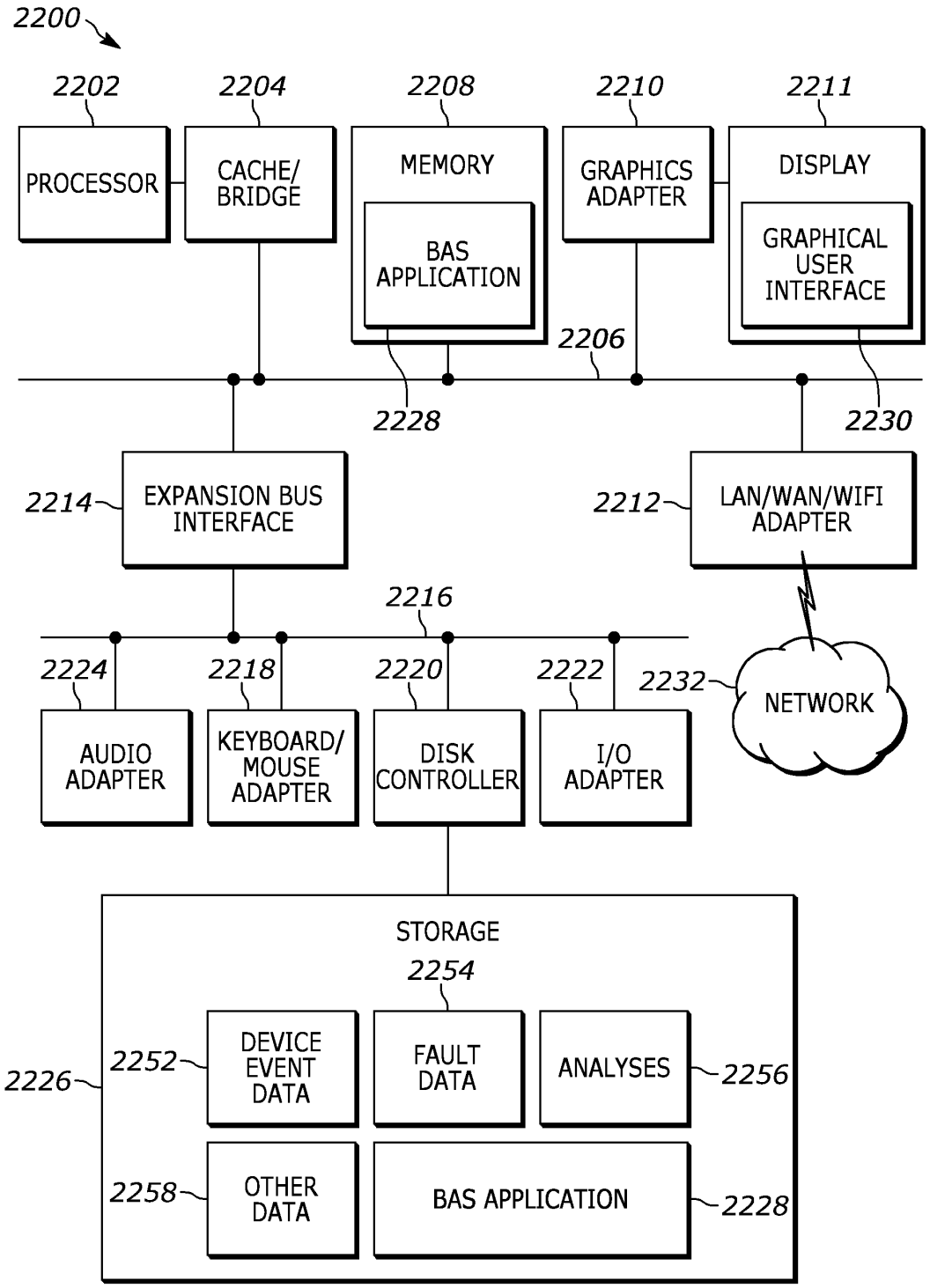
2200
2202
2204
2208
2210
2211
PROCESSOR
CACHE/ BRIDGE
MEMORY
BAS APPLICATION
GRAPHICS ADAPTER
DISPLAY
GRAPHICAL USER INTERFACE
2206
2228
2230
2214
EXPANSION BUS INTERFACE
2212
LAN/WAN/WIFI ADAPTER
2216
2224
2218
2220
2222
2232
NETWORK
AUDIO ADAPTER
KEYBOARD/ MOUSE ADAPTER
DISK CONTROLLER
I/O ADAPTER
STORAGE
2254
2252
DEVICE EVENT DATA
FAULT DATA
ANALYSES
2256
2226
2258
OTHER DATA
BAS APPLICATION
2228

FIG. 22