Ames Research Center

Designing Resilient Engineered Systems with Prognostics Health Management

Figure out operations ahead of Time

Jose Matelli
Kai Goebel

NASA Ames Research Center, Moffett Field CA 94035

Presented at

NIST workshop
Gaithesburg, MD

2018

Prognostics CoE

Engineering System - Cost

- Commitment during Conceptual/Embodiment Design
  - Economic factors
    - Capital cost
      - Optimal configuration
      - Materials
      - ...
    - Life cycle cost
      - Operation
        - Performance
        - Uptime
        - Job/mission completion
      - Maintenance & Repair
        - Scheduled
        - Unscheduled
      - Inventory reduction
      - Defect and rework
  - Safety
    - Impairment of critical functions
- Want: Resilient System
  - Consider various cost elements
    - Downtime (loss of revenue)
    - Cost of mitigation
    - Level of restoration / partial loss of function (reduced throughput/efficiency of operations
    - Ability to foresee/predict and prevent failure (cost of scheduled maintenance/ avoided cost of downtime)

Resilience Quantification

- Downtime
  - Loss of revenue
  - Loss of capability
- Cost of mitigation
- Level of restoration / partial loss of function
  - Reduced throughput/efficiency of operations
- Ability to foresee/predict and prevent failure
  - Cost of scheduled maintenance/ avoided cost of downtime

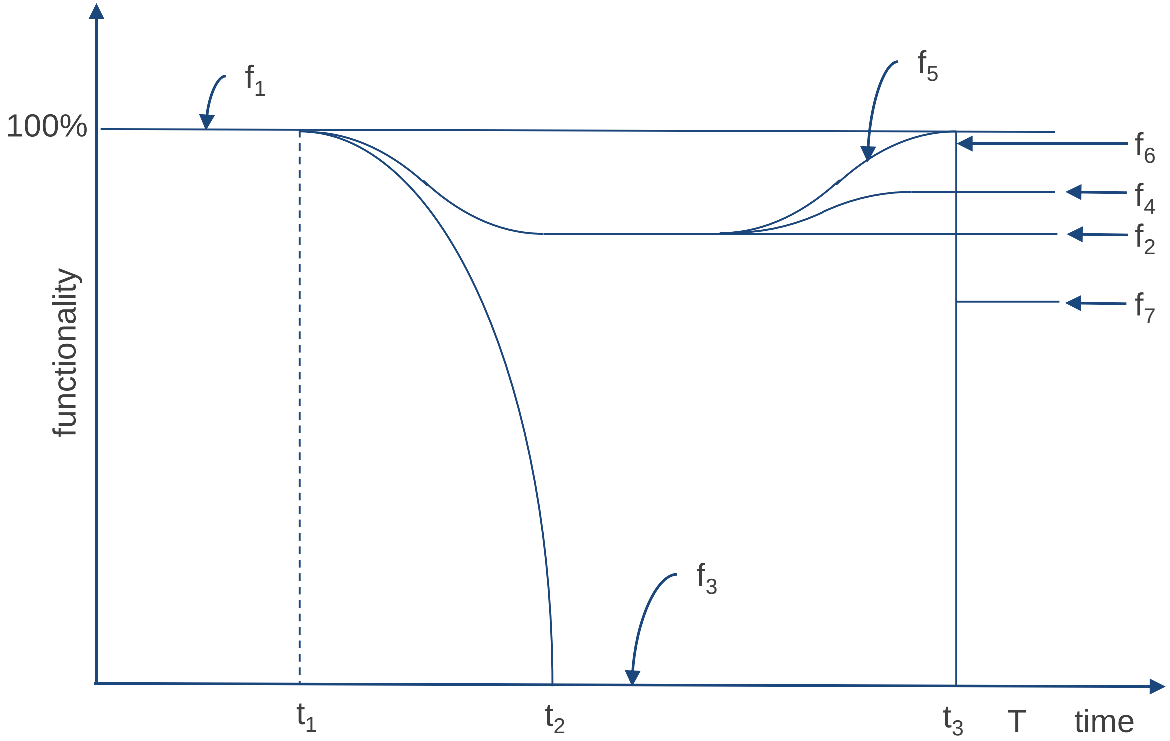
Image credit: http://www.fabricatingandmetalworking.com

Engineering Design

- Complex engineered system (CES): a system composed of densely interrelated subsystems
  - tasked with performing one or more high level functions.
- Design Stages
  - Define requirements
  - Conceptual design
    - Establish function structures
    - Search for solution principles
    - Evaluate against technical and economic criteria
  - Embodiment Design
    - Preliminary layout and form design
    - Select best preliminary layout
    - Refine against techcal and economic criteria
    - Optimize and complete form design
    - Prepare parts list and production documents
  - Detail Design
    - Detail drawings etc.

Image credit: festo.com

Fault Impact Considered



1. Fully functional
2. Fully failed, no recovery
3. Partially failed, no recovery
4. Partially failed, partial recovery
5. Partially failed, full recovery
6. Fully failed, full recovery
7. Fully failed, partial recovery

Example Action to Mitigate Faults

Less PHM

- Let it Fail
- Fix when Broken
- Redundancy
- Fault Masking
- Fault Tolerance
- Modularity
- Predictive Maintenance
- Controls Adaptation
- Dynamic Replanning
- Self-Healing

More PHM

Assess Impact of Failure and Recovery

Evaluate system level cross connections
Determine fault propagation
Assess redundancies/flexibility
Aggregate elements with different units

- Simulation
  - Measure resilience properties
    - For components with different a priori reliability
      - Determine impact of disruption
      - Determine effectiveness of recovery
- Model
  - Rule-based
    - Explicit knowledge about failure propagation.
- Simulation Framework
  - Monte Carlo
    - Consider probability of occurence

Image credit: scs.org

Some Resilience Metrics

- Quantify/ measure impact of fault:
  - Time and magnitude of disruption and level of capability restoration
- Example metrics
  - Ratio of time in resilient operation:

$$p_r(T,\{p_i\}) = \lim_{N\to\infty}(N_r/N)$$

  - Resilient operating time:

$$\bar{r}(T,\{p_i\}) = \frac{p_r(T,\{p_i\})}{N_r}\sum_{k=1}^{N_r} r_k \qquad \{k \mid t_k = T, 0 < r_k \le t_k\}$$

  - Time until failure

$$\bar{f}(T,\{p_i\}) = \frac{1}{N_f}\sum_{k=1}^{N_f} t_k \qquad \{k \mid t_k < T, r_k \le t_k\}$$

  - Ratio of time in failed operation:

$$p_f(T,\{p_i\}) = \lim_{N\to\infty}(N_f/N)$$

  - Average operating time:

$$\bar{t}(T,p_i) = p_f\bar{f} + (1 - p_f)T$$

  - Normalized resilient index:

$$\rho(T,\{p_i\}) = \bar{t}(T,\{p_i\})/T$$

Simulation Setup

- Initiate lifetime T.
- Non-failed component i is randomly assigned as candidate subject to failure.
  - – i has a known probability p_i to work properly.
- At any time t a failure probability $p_b(t)$ is considered
  - – If $p_b(t) \leq pi$, component i does not fail
    - a new candidate to failure is randomly chosen.
  - – If $p_b(t) > pi$, component i fails
    - determine whether this failure propagates to component j.
    - If it does, check whether failure in j propagates to component k and so on, until failure propagation eventually stops.

Simulation Setup contd.

- Run simulation N times to time T
  - p_i attributed to the respective component i.
  - The set of p_i attributed to respective component i is denoted $\{p_i\}$.
- Ideal failure propagation mechanism assures a “fair game”
  - makes sure that the CES differ only in their configuration:
    a. all CES have the same $\{p_i\}$;
    b. $\{p_i\}$ is constant and time-independent;
    c. a failure in a component is instantaneously propagated to any other component connected to the failed component, regardless of the nature of the connection;
    d. a failure in a component propagates to any other component connected to the failed component with a constant, time-independent probability equal to 1;
    e. no partial failure of any component is admitted;
    f. no repair action is taken.

Example: Power Cogeneration Plant

- Generates electric power and heat at the same time
- It has the following elements:
  - Generator (G) coupled to a reciprocating internal combustion engine (E) or gas turbine (GT).
  - Heat from engine exhaust gases are rejected to the environment, as long as heat from jacket water is recovered in a heat exchanger (HEX)…
  - …in order to provide hot water to a single effect absorption chiller (HWAC) which should meet the chilled water demand.
  - Radiator (R) allows the engine to operate when HWAC is out of service.
  - Mechanical-driven chiller (MDC) can be used either for backup or supplement purposes.
  - Cooling tower (CT) rejects heat from condenser of both chillers
  - Heat from turbine exhaust gases is recovered in a heat recovery steam generator (HRSG) in order to provide steam to a double effect absorption chiller (SAC), which should meet the chilled water demand.

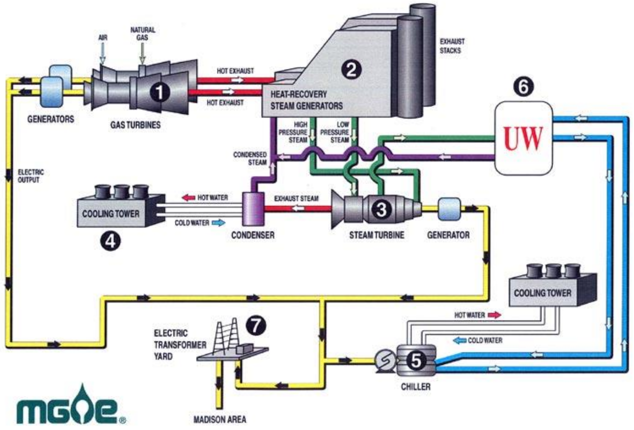
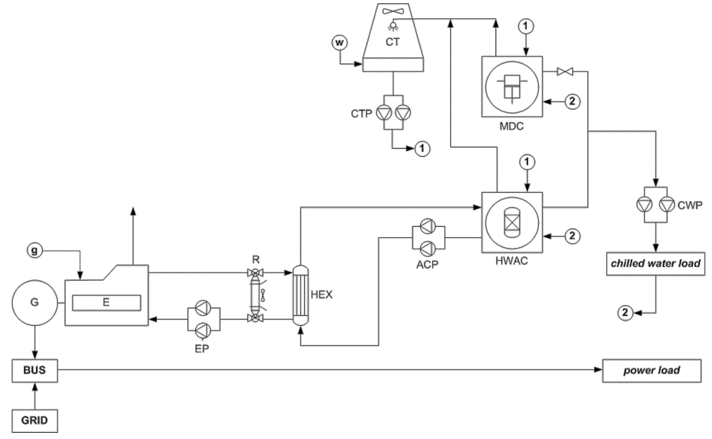


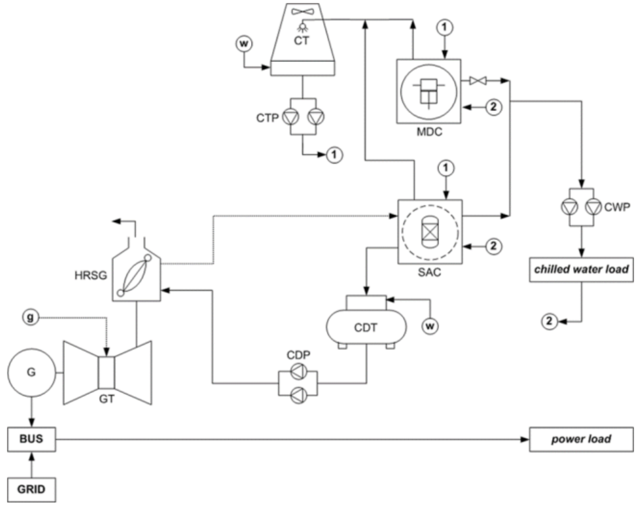
Image credit: Madison Gas&Electric

Cogeneration Plant Design Variations

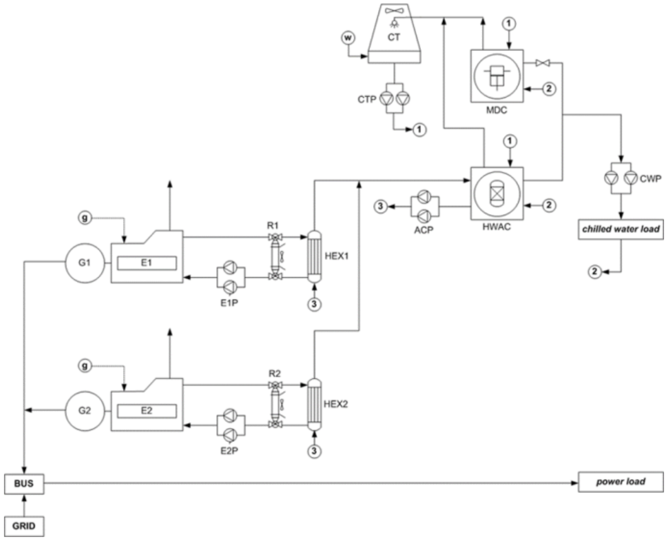
C#1



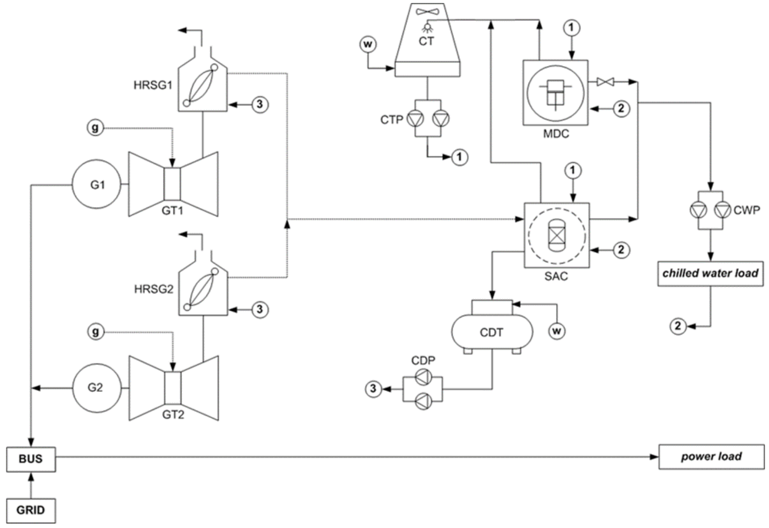
C#3



C#2



C#4



Specific Fault Assumptions

- Permanence
  - Once fault is present, it will stay
    - Can only evaluate some resilience properties
    - But sufficient for illustrative purposes
- Magnitude
  - Fault is either present or not
    - No partial fault in this version
- Two Fault Probabiliy scenarios considered
  - Are all the same
    - p_i = 0.9995 for all components.
  - Are different
    - p_i = 0.9985 for pumps;
    - p_i = 0.9990 for heat exchangers;
    - p_i = 0.9995 for all other components.

Image credit: Wikipedia.org

Results

Case	Resilience metric	Most resilient	→	→	Least resilient
Equal p_i T = 8760 h N = 3000	Average resilient time (h)	C#2 (4245.7)	C#4 (3658.5)	C#1 (3187.5)	C#3 (2889.5)
	Average time until failure (h)	C#2 (5197.6)	C#4 (5116.0)	C#1 (5056.7)	C#3 (4848.6)
	Average operating time (h)	C#2 (7592.7)	C#4 (7252.6)	C#1 (7051.6)	C#3 (6703.9)
	Prob. of resilient operation	C#2 (0.654)	C#4 (0.568)	C#1 (0.516)	C#3 (0.456)
	Prob. of failing	C#2 (0.328)	C#4 (0.414)	C#1 (0.461)	C#3 (0.526)
	Normalized resilience index	C#2 (0.867)	C#4 (0.828)	C#1 (0.805)	C#3 (0.765)
Different p_i T = 8760 h N = 3000	Average resilient time (h)	C#2 (4082.1)	C#4 (3658.5)	C#1 (2985.3)	C#3 (2919.7)
	Average time until failure (h)	C#2 (5449.0)	C#4 (5334.0)	C#1 (5113.0)	C#3 (4913.0)
	Average operating time (h)	C#2 (4832.6)	C#4 (4476.4)	C#1 (3559.5)	C#3 (3542.0)
	Prob. of resilient operation	C#2 (0.550)	C#4 (0.508)	C#1 (0.406)	C#3 (0.404)
	Prob. of failing	C#2 (0.448)	C#4 (0.489)	C#1 (0.594)	C#3 (0.596)
	Normalized resilience index	C#2 (0.552)	C#4 (0.511)	C#1 (0.406)	C#3 (0.404)

More Results

$$\bar{f}/T \lesssim \rho \leq 1$$

Resilience index comparison.

Case	C#	Res. index
Equal p_i T = 8760 h N = 3000	2	0.867
	4	0.828
	1	0.805
	3	0.765
Different p_i T = 8760 h N = 3000	2	0.831
	4	0.809
	1	0.753
	3	0.738

C#3 is the least affected by components with low p_i: resilient index decreased 2.32%.

C#1 is the most affected by components with low p_i: resilient index decreased 6.48%.

Conclusions

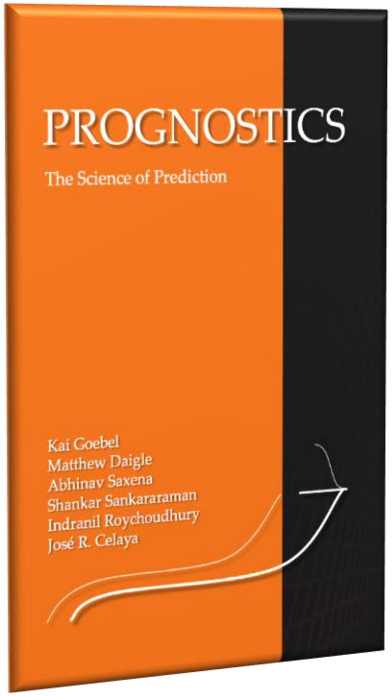
- For optimally resilient systems
  - Embrace PHM as an active element within design of systems
  - Assess performance during conceptual design to best understand impact of PHM
- Proposed framework
  - allows early assessment of resilience
  - Resilience is a property of the system configuration.
- Framework agnostic of particular design
  - Potential to be used with *any* CES.
- Ability to provide failure rationale can provide insight to design team.
  - Redundancy is not always the best alternative to increase resilience.
- Can also use approach to assess retrofit solutions

Questions!

Thank You !

More Stuff

- Book
  - *Prognostics: The Science of Prediction* Goebel et al.



PROGNOSTICS

The Science of Prediction

Kai Goebel
Matthew Daigle
Abhinav Saxena
Shankar Sankararaman
Indranil Roychoudhury
José R. Celaya

- Prognostic Data Repository
  - Run-to-failure data
    - Bearings, batteries, composite structures, jet engines, milling machine,
  - Find the data at: prognostics.nasa.gov