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Smart Rehabilitation and Maintenance in Civil Engineering for Sustainable Construction

Leveraging AI in Asset Maintenance

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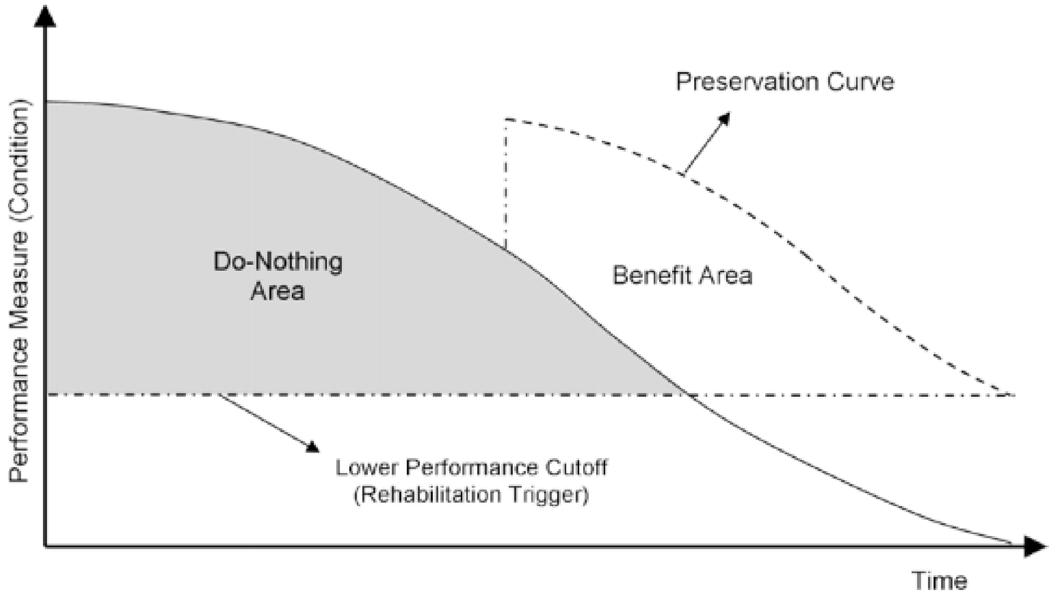
Topics

1. Background
2. Asset Maintenance Process
3. Fault Diagnosis & Prognosis
4. AI use cases
5. Conclusion.

1. Background

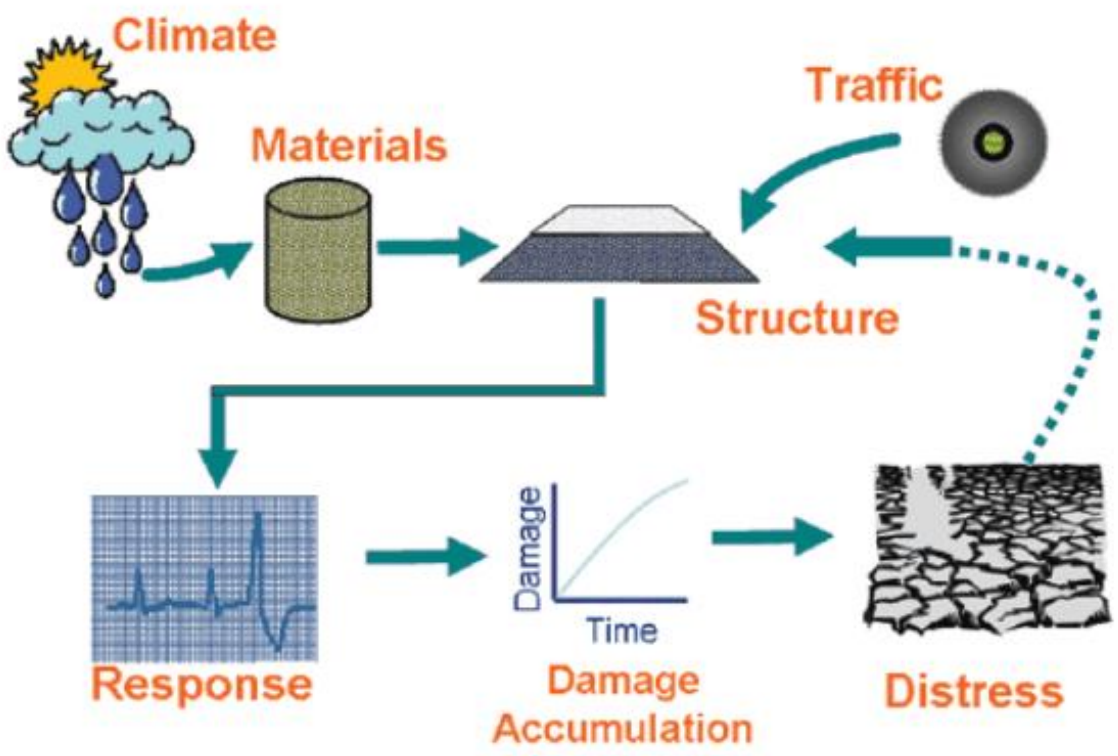
Asset Performance



from Developing pavement performance models (TRB 2017)

- Performance curve
  - predicts how performance degrades with time and/or use
- Asset can show early signs of failure
- Failure threshold
  - A lower cutoff on performance which signals failure is imminent
  - rehabilitation must be done soon
- Rehabilitation
  - Restore asset to original performance
  - Value of asset is restored.

System context of asset performance



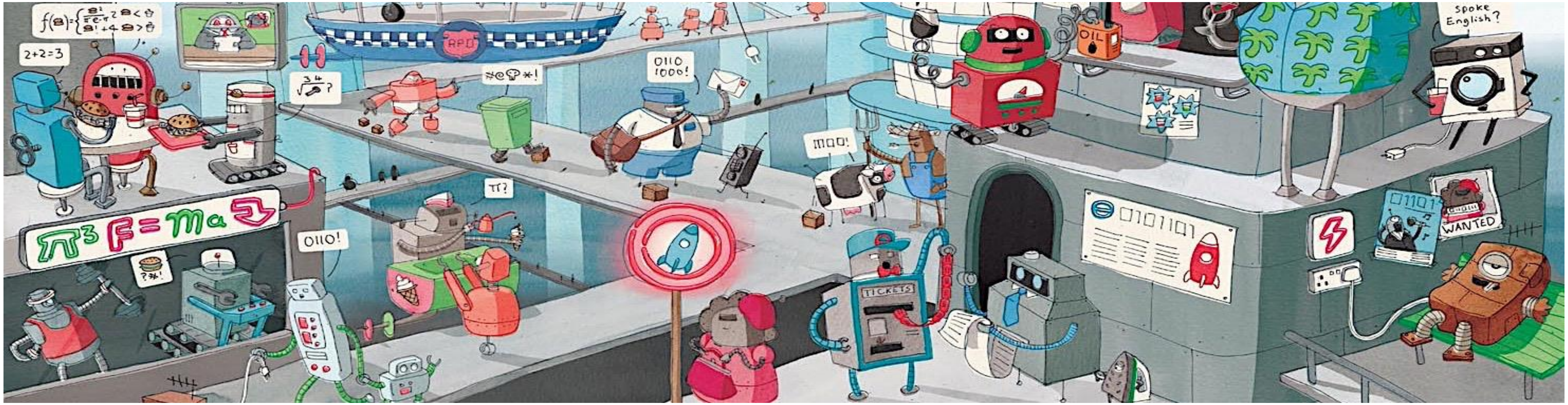
from Developing pavement performance models (Kargah-Ostadi: TRB 2017)

- Multi-causation
  - Degradation of performance is due to many factors
  - No two assets will be identical on all these factors
- Causation is not one-way
  - A factor may influence the effect of another factor on the response
  - +ve / –ve feedback loops among the factors and the response.

AM tasks & decisions

- What asset to maintain
- How to detect faults which lead to asset failure
- How to assess health condition and diagnose faults
- What limits and thresholds should be set for timely action
- What is the prognosis
- What is the appropriate maintenance action
- How to balance value preservation *vs*. maintenance cost over the asset life-cycle
- Which AM strategy to create cost effective programs.

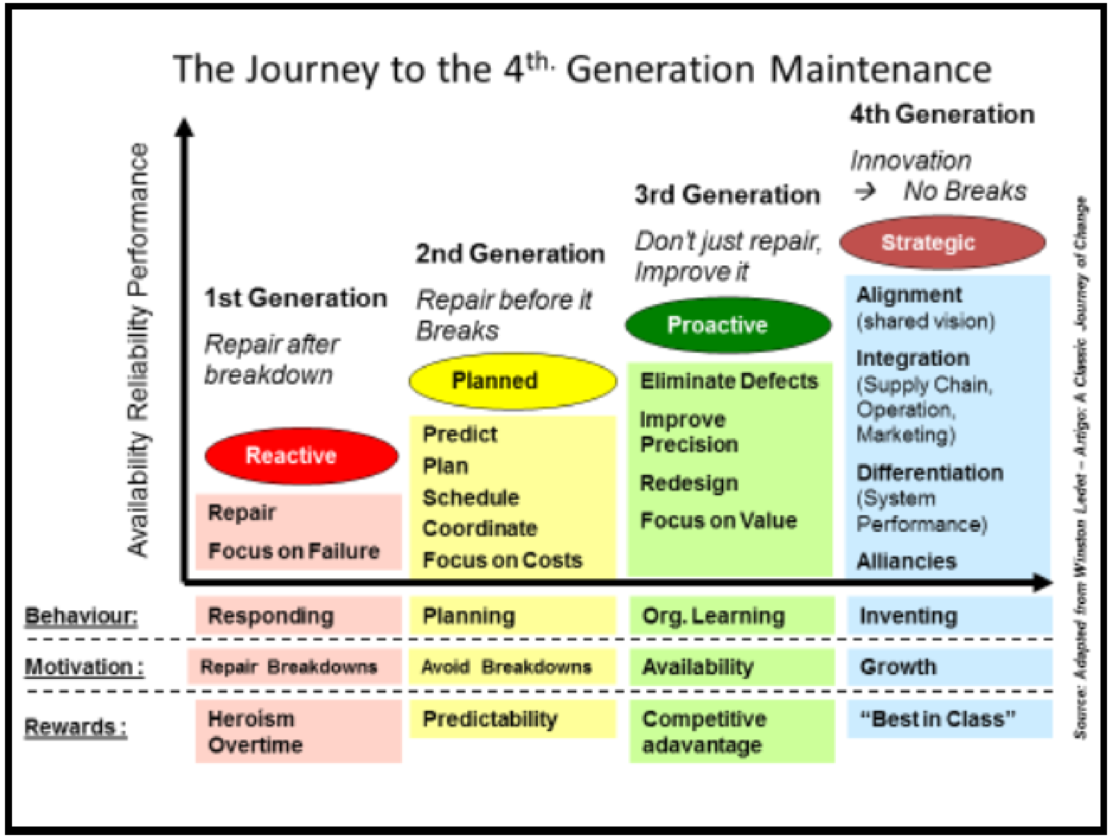
Shift of emphasis



- Increasing complexity
    - Both asset functions and technical systems
- More interdependency between systems
- Internet of Things
    - Better sensors, communications and computing power create opportunities.

- Shift
    - From single asset to system to ‘system-of-systems’
    - From data to information processing
    - From functionality to service quality.

Asset Maintenance Management

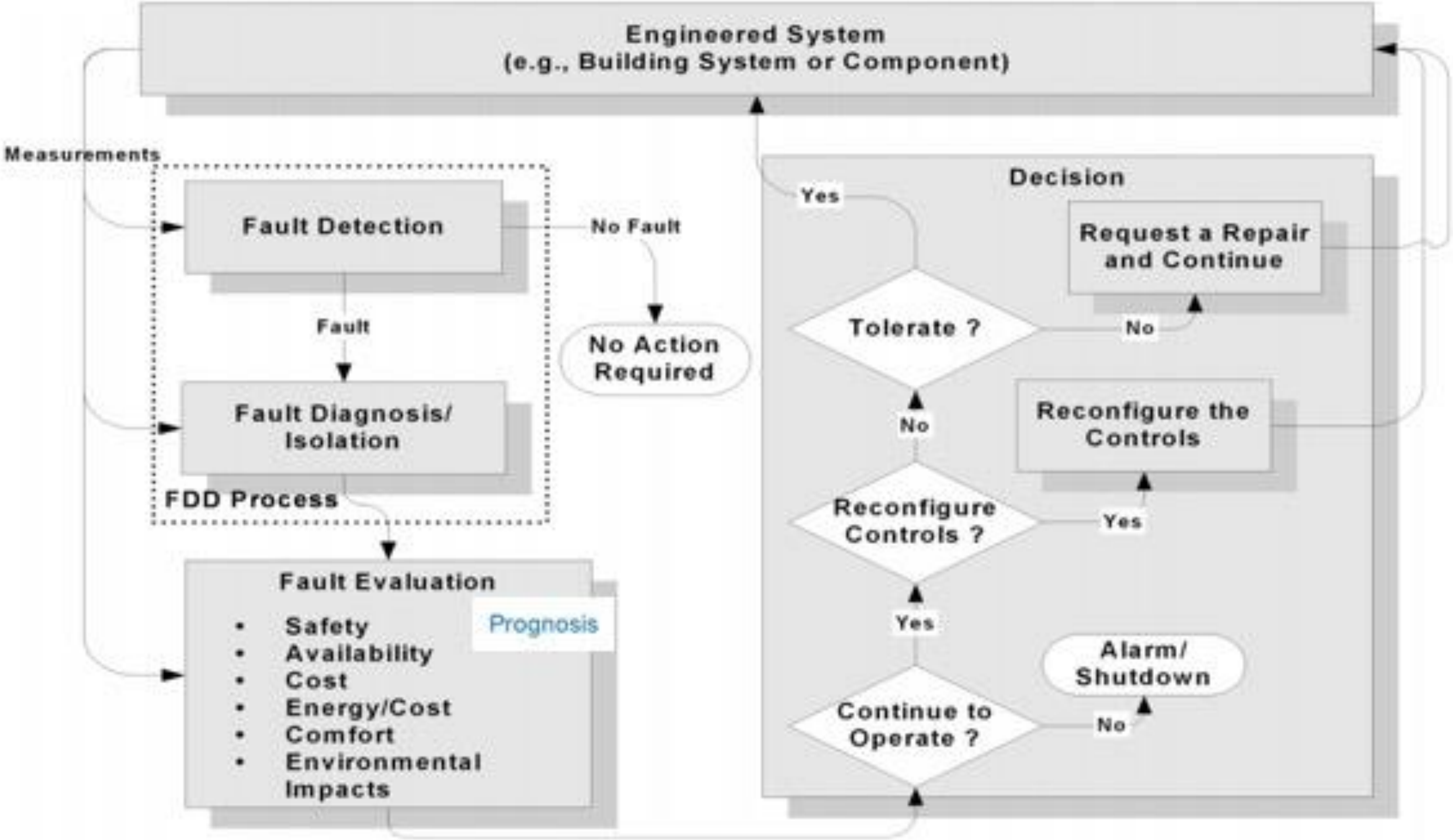


from Moubray(1991)

- Strategy for the continuous improvement of the
  - availability, safety, reliability and longevity of physical assets in systems, facilities, equipment or processes
- Goal & process alignment
  - Technical + business aspects
  - Balance asset value preservation *vs.* maintenance cost
- Objective
  - Assets shall be *available* when required and can *fulfil their function safely* and *reliably* in conformance with specified *requirements*.

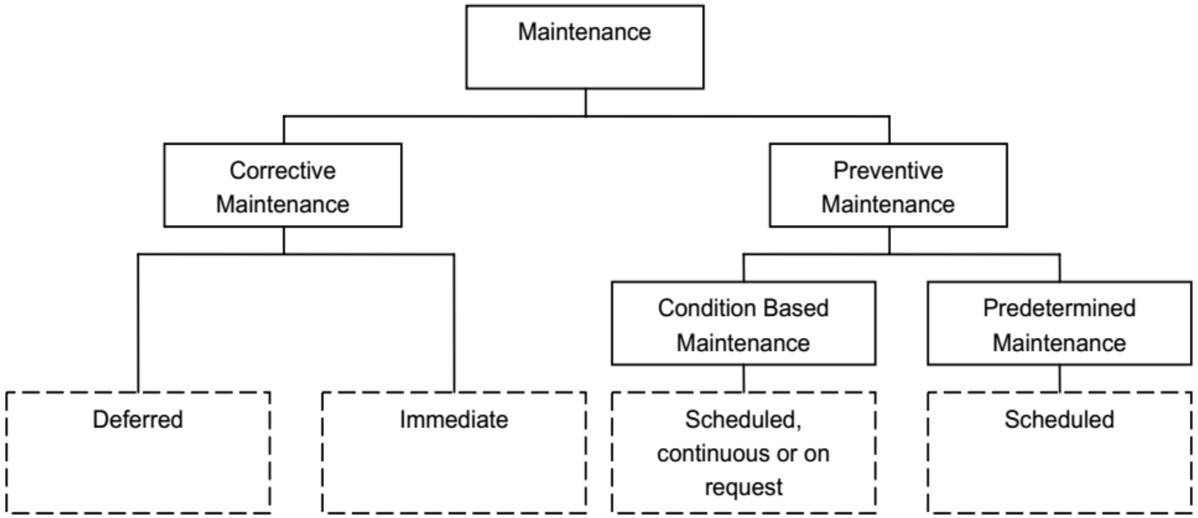
2. Asset Maintenance Process

Asset Maintenance framework



from Katipamula (2005)

Maintenance strategies

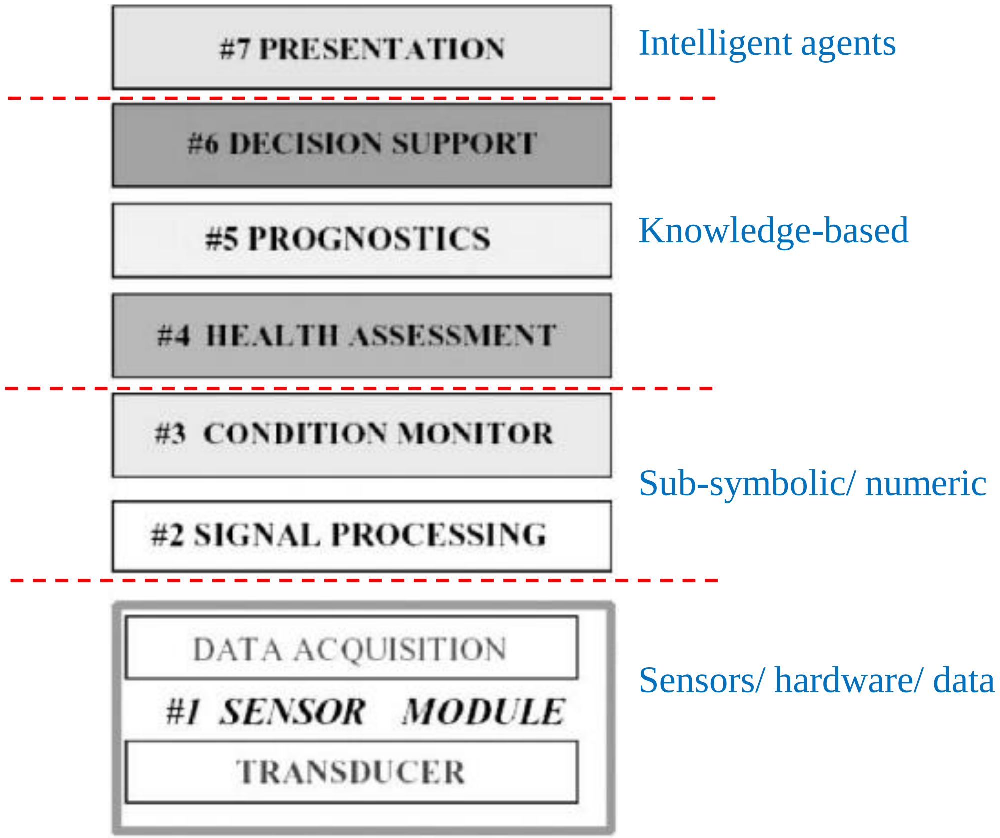


from Bengtsson (2007)

- Corrective
  - Action after event (critical warning, failure)
  - Possible actions:
    - Defer, partial of complete repair, Rehabilitate, Replace
- Preventive
  - Time-based or X number of uses
  - Pre-empt failure
  - Costly
- Predictive
  - Condition based
  - Needs monitoring to determine state of ‘health’.

Architecture of AM system

- Multi-layered architecture
  - Each layer processes data/ information in its own way to fulfill its role
  - Each layer receives information from the previous one
- Level of information abstraction
  - From sensor data in the form of analog or digital signals, to sub-symbolic numeric data, to knowledge concepts at the symbolic level
- Information processing
  - Numeric routines for signal processing
  - Sub-symbolic computation with Artificial Neural Nets
  - Logical reasoning with expert systems
  - Co-planning with intelligent agent systems.



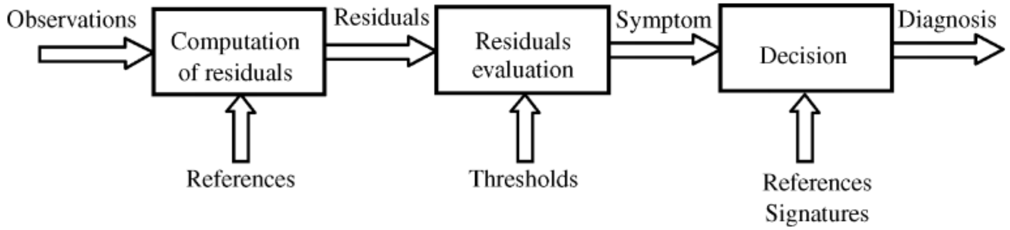
from Kothamasu (2006)

3. Fault Diagnosis & Prognosis

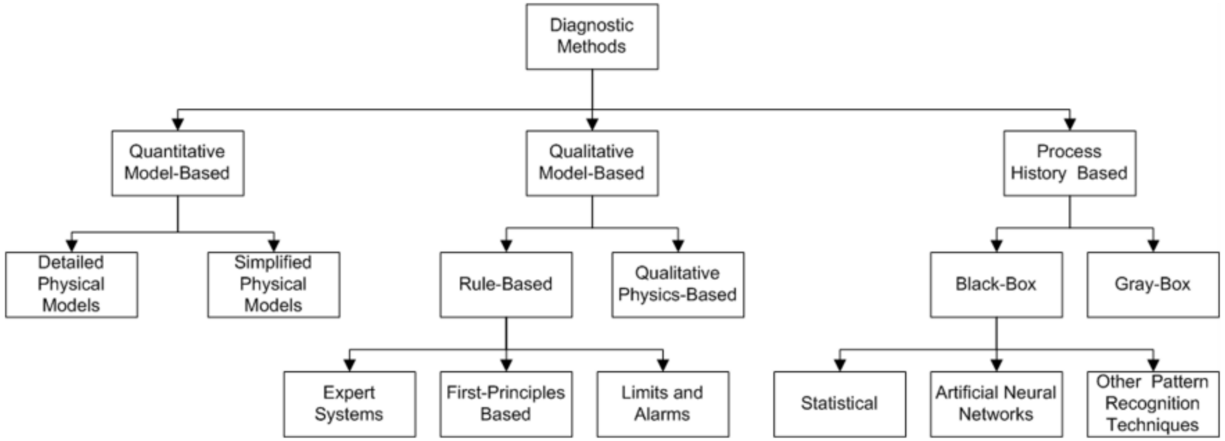
Fault diagnosis methods

- Diagnosis
  - Is there a fault (detect)
  - What is the fault (identify)
  - Where is it (isolate)
- Methods
  - Data-driven
    - Statistics
    - ANN
    - Signal analysis & pattern recognition
  - Model-based
    - First principle physics
    - Qualitative physics
    - Knowledge of probable cause-effect.

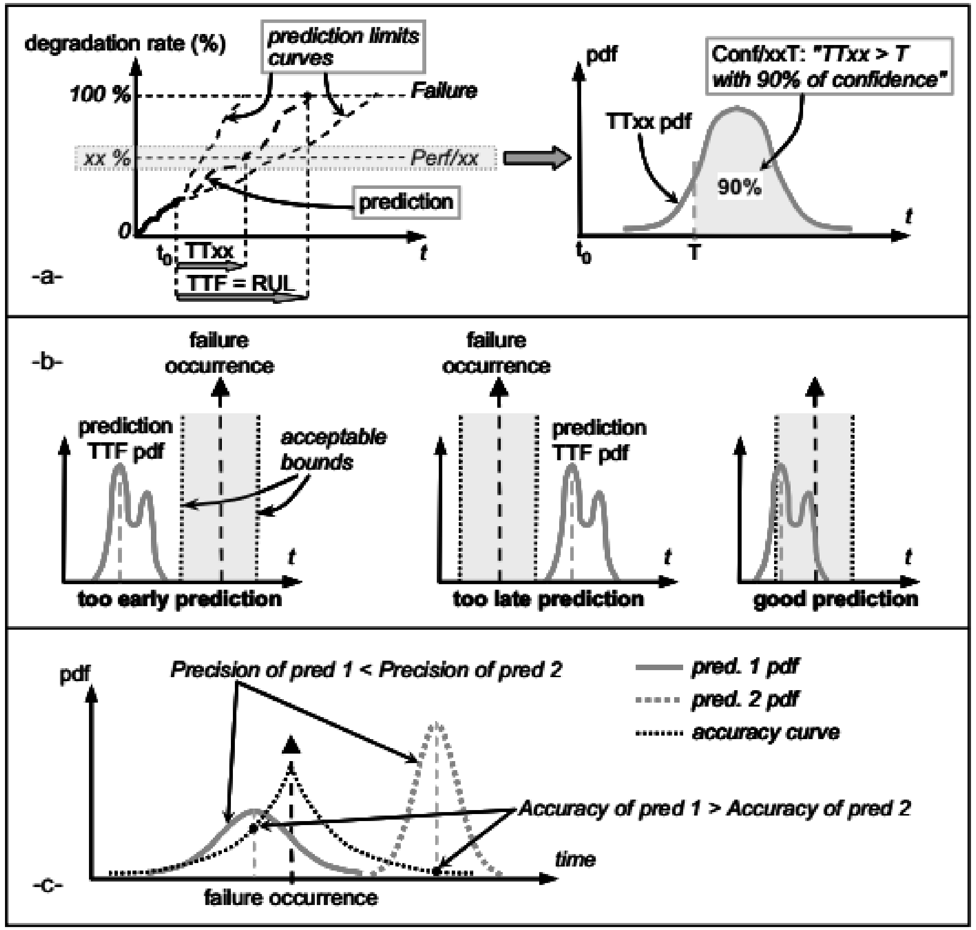
from Hissel (2004)



from Katipamula (2005)



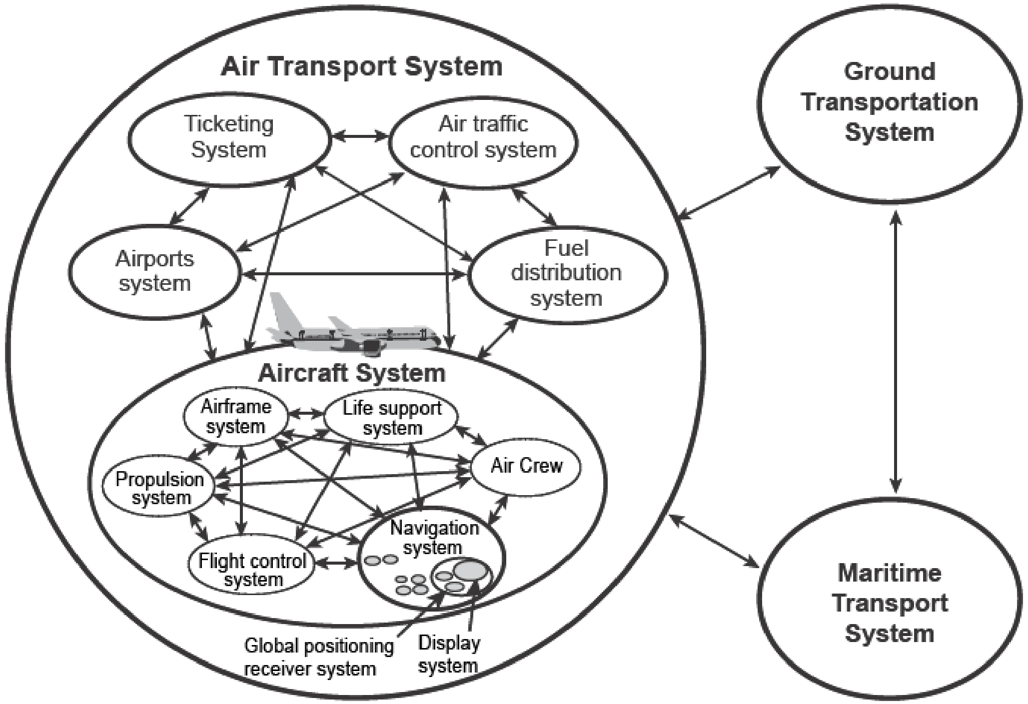
Prognosis: accuracy & precision



from Dragomir (2009)

- Prognosis
  - Prediction of the future state of health given current state and proposed actions
  - or prediction of when failure will occur
- Predictions
  - Probability distribution of expected time to failure or remaining useful life (RUL)
- Accurate
  - Actual time falls within pdf. Don't want to be too late or too early in the prediction
- Precise
  - Pdf is narrowly defined, otherwise prediction is not actionable.

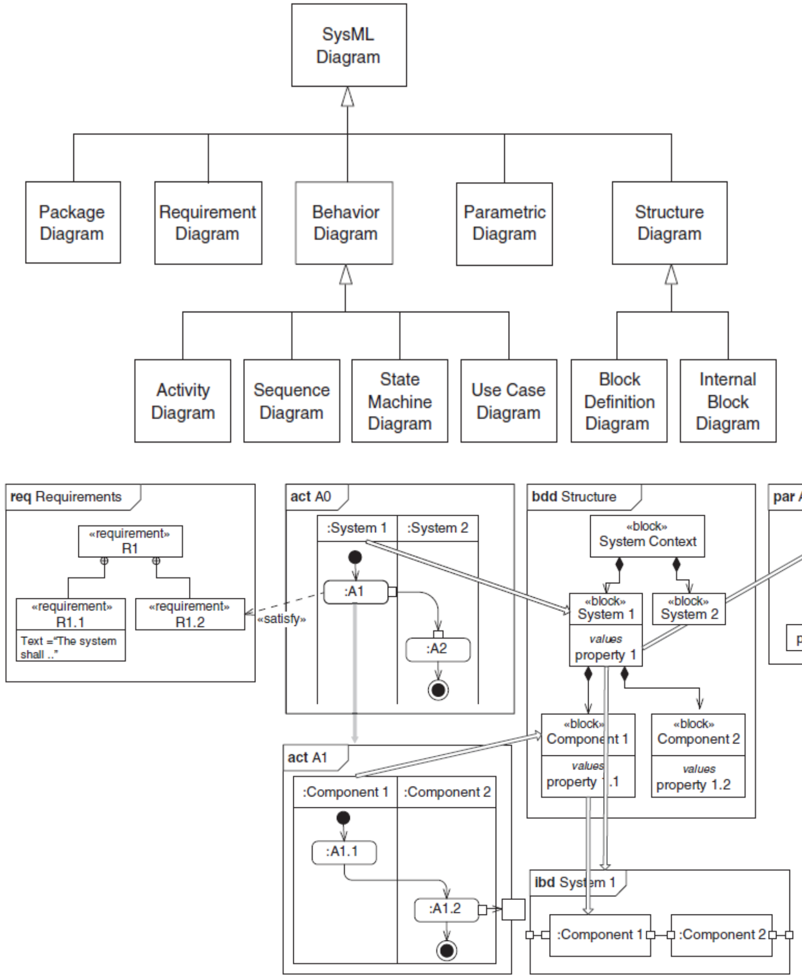
System concepts



from INCOSE SE Handbook

- Systems are hierarchical
- Purposeful design: functionality
- Systems interact: emergence
  - Reliability, availability, safety, maintainability
- A ‘system’ is a conceptual device to describe reality
  - Structural composition
  - Behavior.

System description language: SysML



from Friedenthal (2008)

- Description of asset as a system
  - For fault diagnosis & prognosis
  - Structure + behavior
  - Requirements + parametrics
- Machine + human readable
  - Computer-aided maintenance
- Replace paper documents
  - One consistent database, many data views.

4. AI use cases

AI techniques (1)

Technique	**Task**	**Strength/ *Weakness***
Artificial Neural Networks	Fault diagnosis Prognosis Cause-and-effect analysis TTF prediction Supervised data classification Clustering Function approximation	Simple generic structure – simple to apply Data-driven – no model needed ANNs can approximate any calculable function to an arbitrary degree of precision *Needs a lot of examples for training* *Can be over-trained on the data and become poor at generalization*
Deep Learning	Image/ signal / pattern recognition	(Massively) data-driven – no model needed Does not need application of special image/ signal analysis techniques to extract training features *Needs significantly more computational power and storage to train the network.*

AI techniques (2)

Technique	**Task**	**Strength/ *Weakness***
Knowledge-based / rule-based expert systems (KBES)	Fault diagnosis Prognosis Planning Cause-and-effect analysis	Encodes human expert domain knowledge in a machine executable yet human readable form Can solve problems in a logical but non-procedural way *Knowledge transfer from experts can be a bottleneck* *Rules must be 'tuned' to optimize inference* *Fails to reach conclusions when presented with concepts beyond its rule base*
Fuzzy logic systems (FLS)	Fault diagnosis Prognosis Planning Cause-and-effect analysis	Has many of the same strengths as KBS Handles uncertainty and ambiguity in knowledge application in human-like way More robust than KBES with crisp rules *Rules and definition of fuzzy sets must be tuned.*

AI techniques (3)

Technique	**Task**	**Strength/ *Weakness***
Case-based reasoning (CBR)	Fault diagnosis Planning	Uses past experience in the form of structured 'cases' to solve similar problems Can adapt old cases to new problems *Outcome is sensitive to method of case retrieval*
Genetic Algorithms (GA)	Optimal connection weights of ANN Model calibration Maintenance program & schedule optimization	Very versatile for search & optimization problems Does not need the objective function to have derivatives *Can be trapped in a local optimum.*
Reinforcement Learning (RL)	Optimal maintenance policy	Learns from feedback 'on-the-job' – does not need large number of training cases or historical data Does not need a model of the environment – only reward signals Guaranteed to converge to optimal policy if sufficient time is given *Can be computationally expensive if state-action space is large.*

Artificial Neural Network: structure

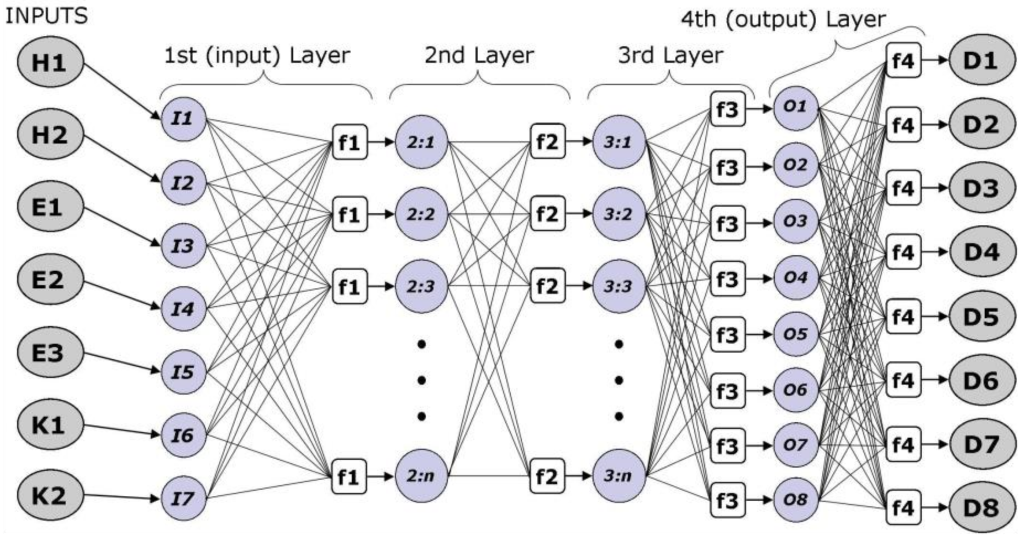
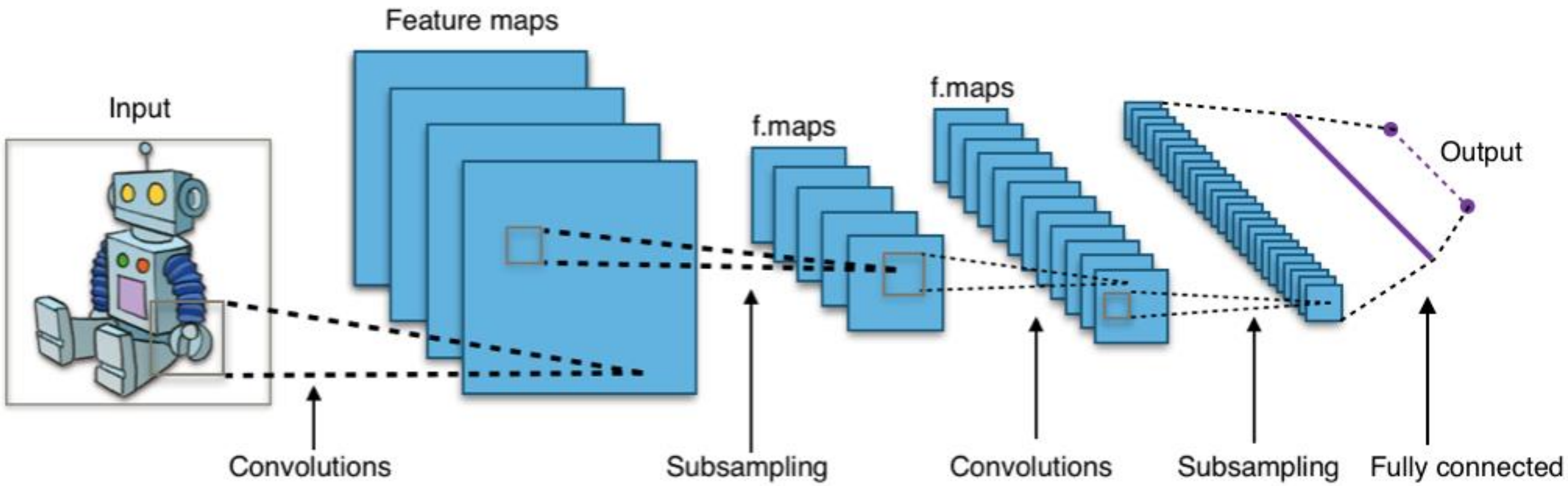


Figure 2-8. A four-layered feed-forward ANN

from Ostadi (2013)

- ANN architecture
  - Input layer of neurons
  - At least one or more hidden layer of neurons
  - Output layer of neurons
  - Connection weights between neurons in adjacent layers
- Fault features are used as inputs
  - Sensor data is pre-processed by signal processing or statistical algorithm
- Output is a fault type, location or likelihood of failure
- ANN feeds-forward during operation
- Training of ANN
  - backpropagation of residual errors
  - adjustment of connection weights.

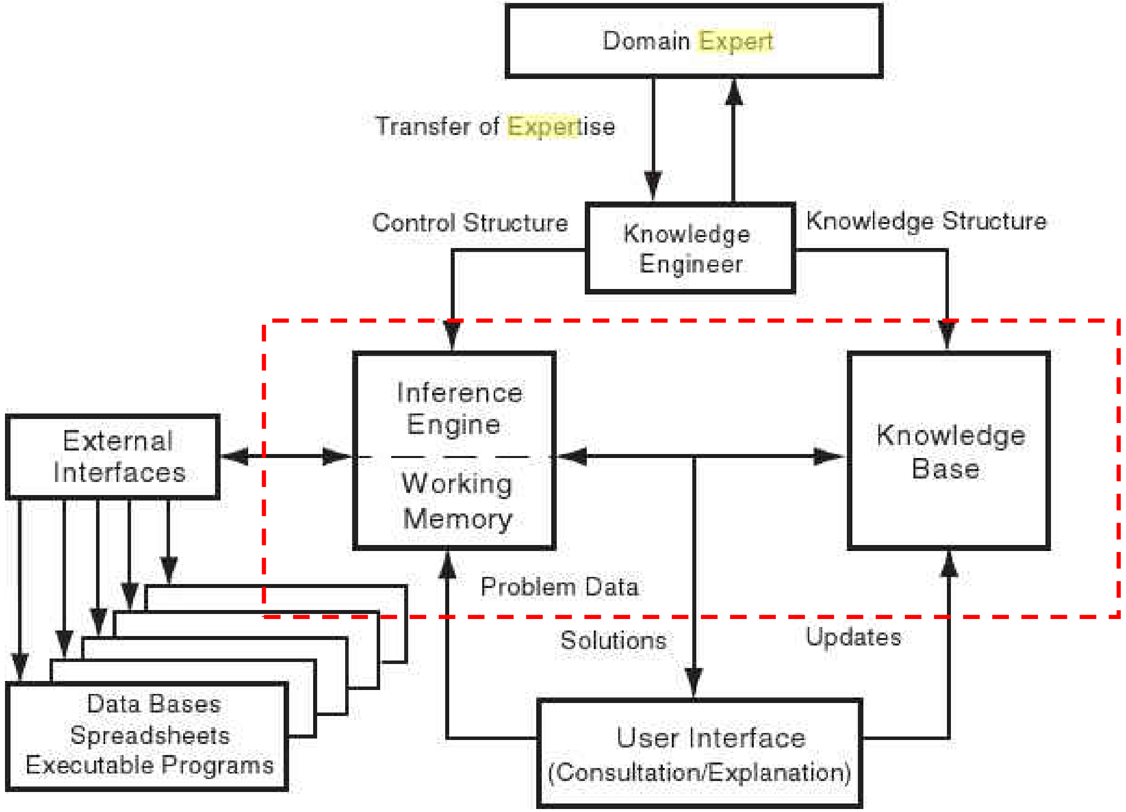
Deep Learning Network structure



- Blocks of neurons arranged in layers
- Each block computes higher level features from the preceding block
- Neurons in each layer connected only to a small focal region in preceding block.

- Feeds-forward like ANN in operation
- Training is by backpropagation of errors or reinforcement learning
- Requires massive data & computing power
- Works directly on signal data
  - No manual feature extraction is needed.

Rule-based Expert System

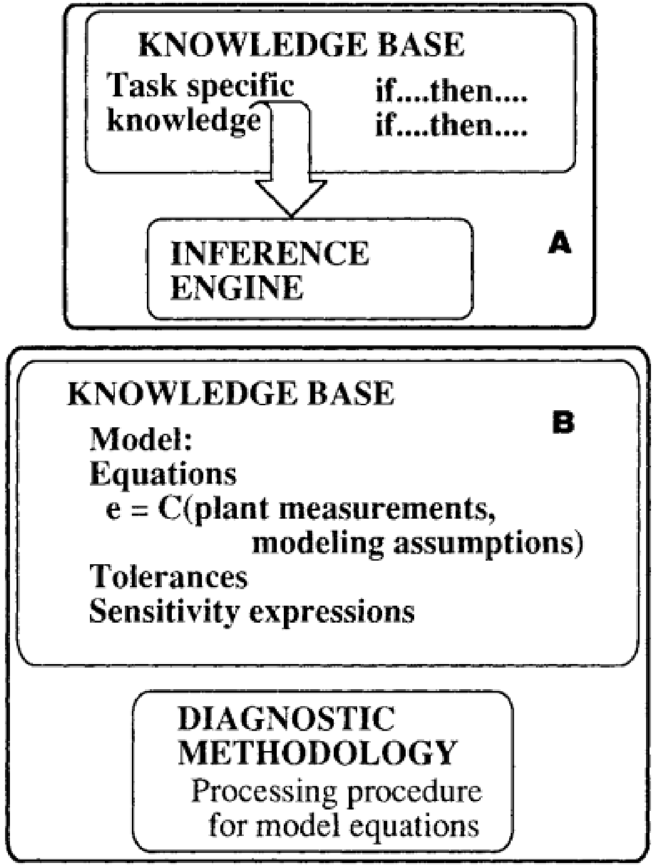


from Petti (1990

IF:	mass balance is high
AND:	**feed2** valve curve is high; calculated value agrees with valve curve.
NOT:	**feed1** flow sensor is high; level sensor is stuck; **prod** flow sensor is low; expecting "strange behavior."
THEN:	**feed2** flow sensor is high.

- Diagnosis expertise
  - Encoded as if-then rules
  - Both causal & control knowledge is encoded
- Rule firing
  - Bottom-up: from data to conclusions
  - Top-down: from hypothesis to supporting evidence
- 'Shallow' knowledge.

Knowledge-based Expert System

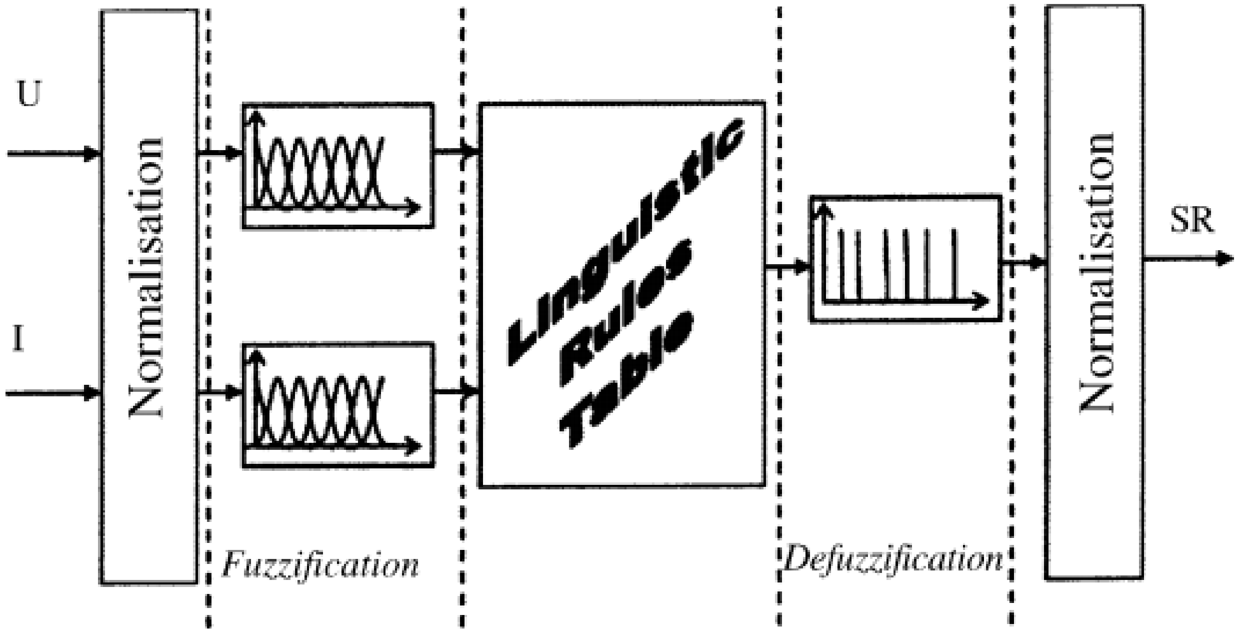


a. Compiled knowledge-based system; process- and task-specific knowledge base with general inference engine
b. Diagnostic model processor; process-specific deep knowledge base with task-specific diagnostic methodlogy

from Petti (1990

- Retains diagnostic if-then rules
- Adds 'deep' knowledge
  - Process equations
  - Rich description of objects in the application domain.

Fuzzy Logic System

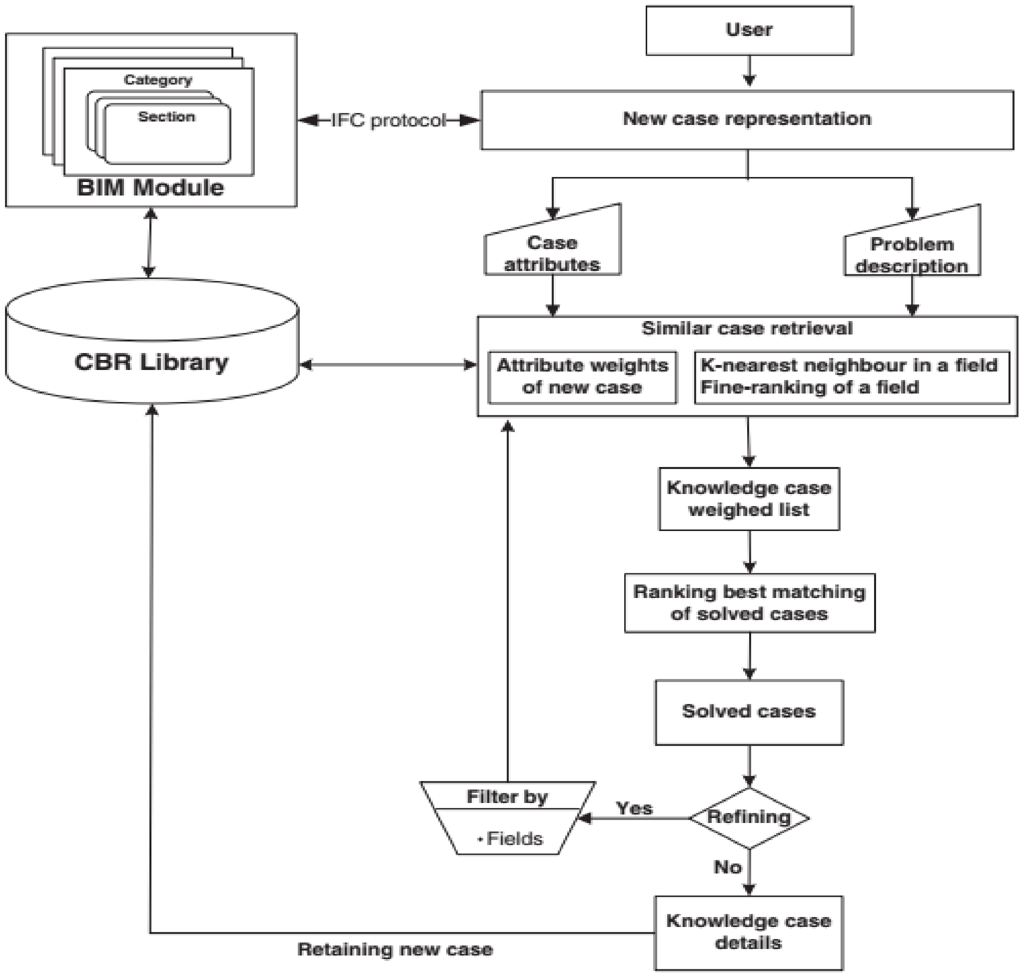


from Hissel (2004)

- Data is encoded as fuzzy value using linguistic variables
- If-then rules use linguistic variables for reasoning
- Fuzzy inference engine propagates fuzzy values using fuzzy version of logic operators
- Result is defuzzified for presentation
- Fuzziness overcomes 'brittleness' of crisp if-then rules.

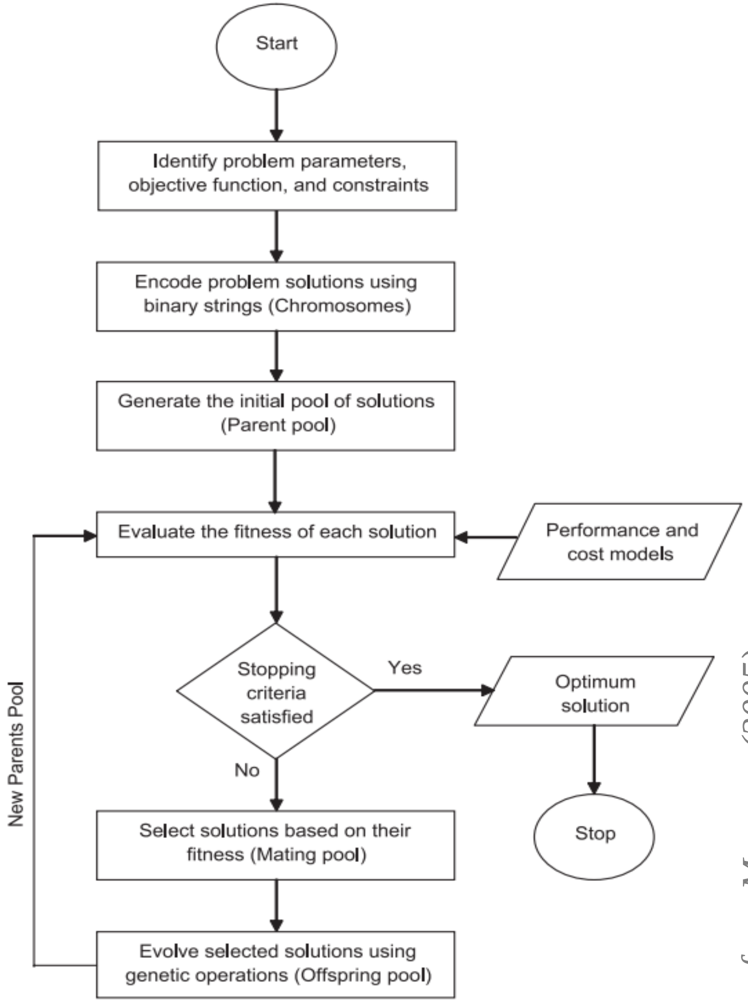
Case-based Reasoning

- Structured case
  - encode past experience in solving particular problems
  - Case fields: symptoms, exclusions, diagnosis, remedy, efficacy, side-effects and level of success obtained
- Query case
  - Matched against cases in case-base
  - Case retrieval finds k-closest matches using similarity measure defined over case fields
  - Remedy of retrieved case is adapted to fit particulars of query case
  - Adapted case is recorded into case base once feedback is received.



from Motawa (2003)

Problem Solving using Genetic Algorithms

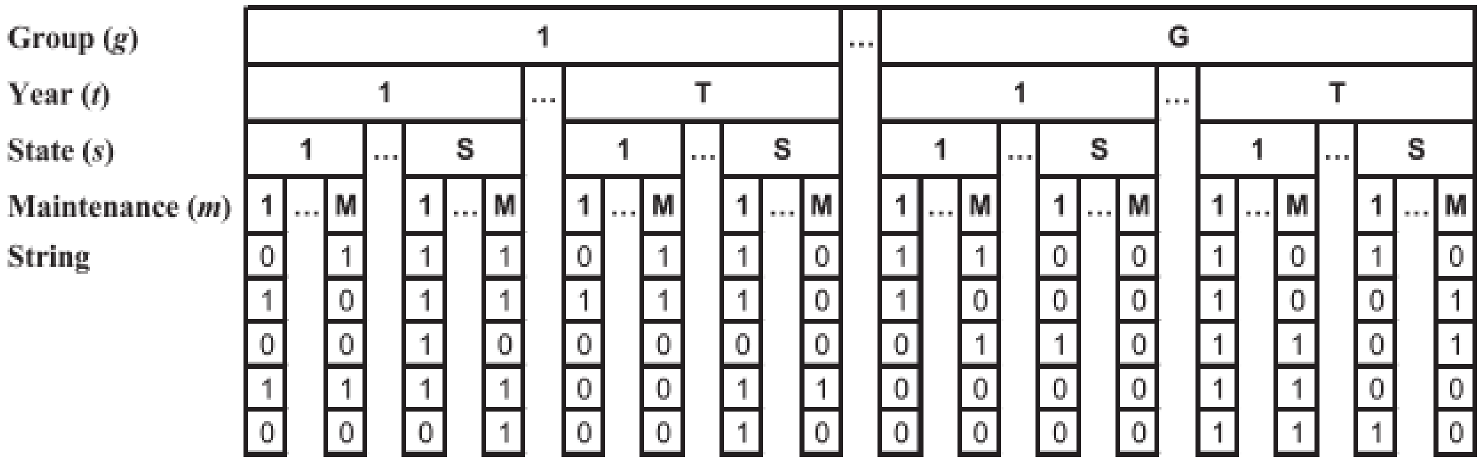


from Morcous (2005)

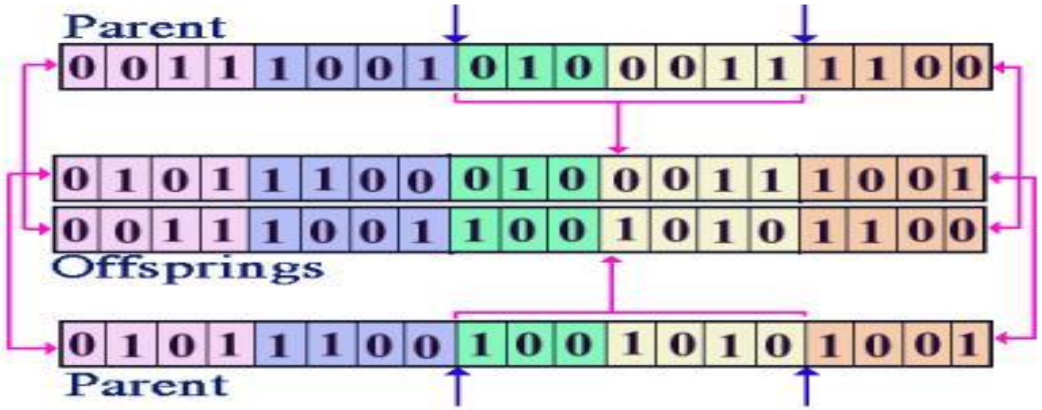
- Iteratively evolves
  - a population of solutions, each of which is a solution to the problem
  - selection pressure forces the population to converge to the optimum
- Key GA operations
  - Selection for mating & reproduction
  - Mating is implemented as crossover, creating novel solutions from current gene pool of parents
  - Mutation perturbs genes randomly
- Very versatile
  - Does not need explicit mathematical function
  - Particularly suited for search & optimization problems.

GA chromosome string structure

- Chromosome string
  - Encodes values at each gene position that are the solution to the problem
- Fitness evaluation
  - After decoding, gene values are substituted into the objective function to determine fitness of chromosome string
  - Fitness determines chance of mating
- Crossover operation
  - Exchanges portions of chromosome string between cut positions to create new individuals
- Mutation operation
  - Randomly perturbs gene values with some probability.



from Morcous(2005)

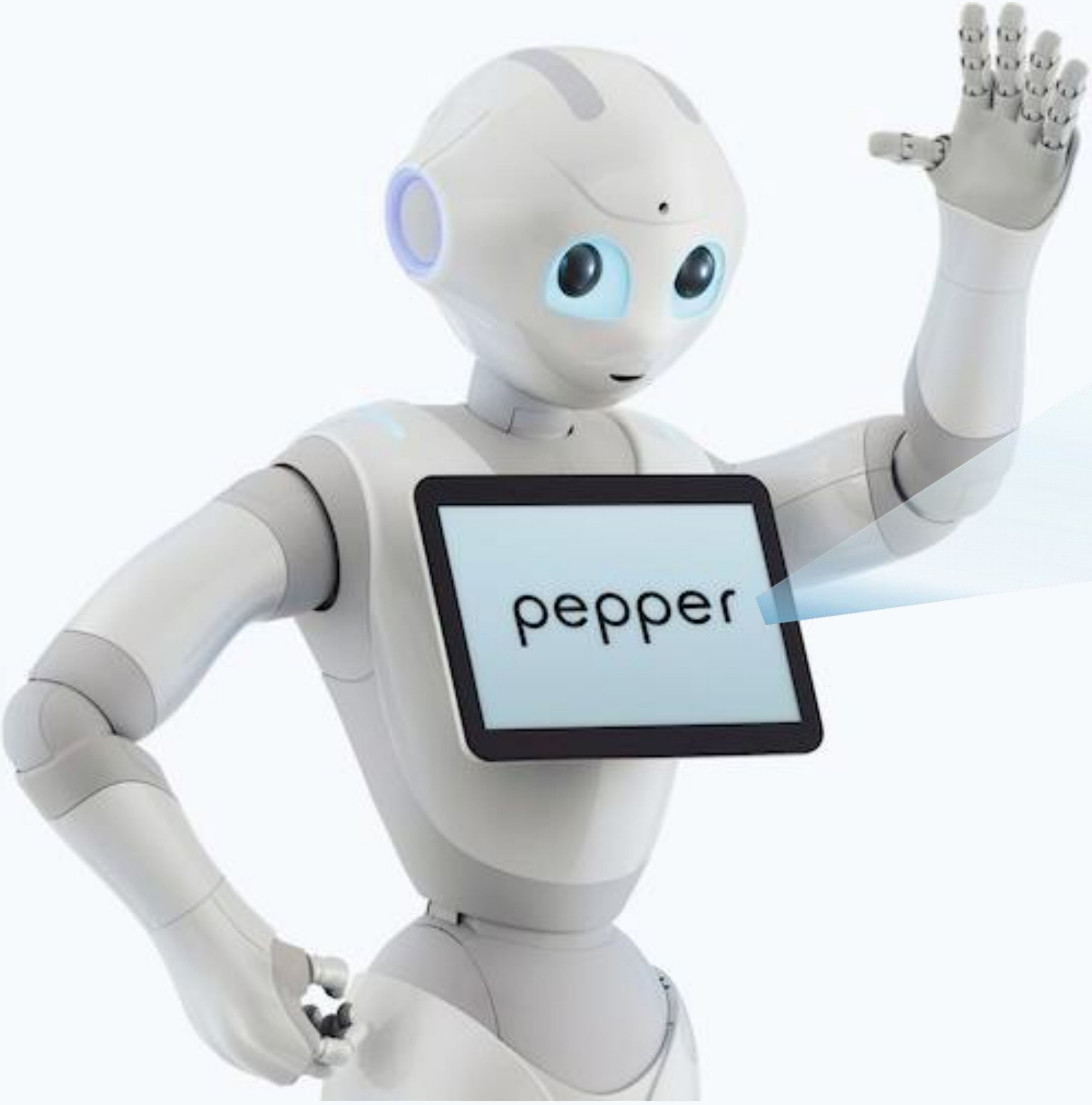


Conclusion (1)

- Increasing technical & system complexity creates greater demand on asset maintenance
- Task focus shifts: from functional to information and systemic aspects
  - Align technical + business goals among different agents
  - Balance asset value preservation *vs.* maintenance costs
- Failure diagnosis, prognosis and maintenance decisions exhibit many information-centric aspects
- Asset maintenance requires an appropriate strategy.

Conclusion (2)

- AI is an attempt to simulate human competencies in information & cognitive tasks
- AI capabilities include
  - classification, clustering, pattern recognition
  - cause-effect reasoning, fuzzy reasoning
  - case recall, planning & decision making
  - search & optimization
  - learning
- AI technology
  - becoming increasingly accessible for adoption
  - can be leveraged in AM tasks depending on capability.



Thank you!