Collaborative Research: Quantitative Reliability Prediction in Early Design Stages

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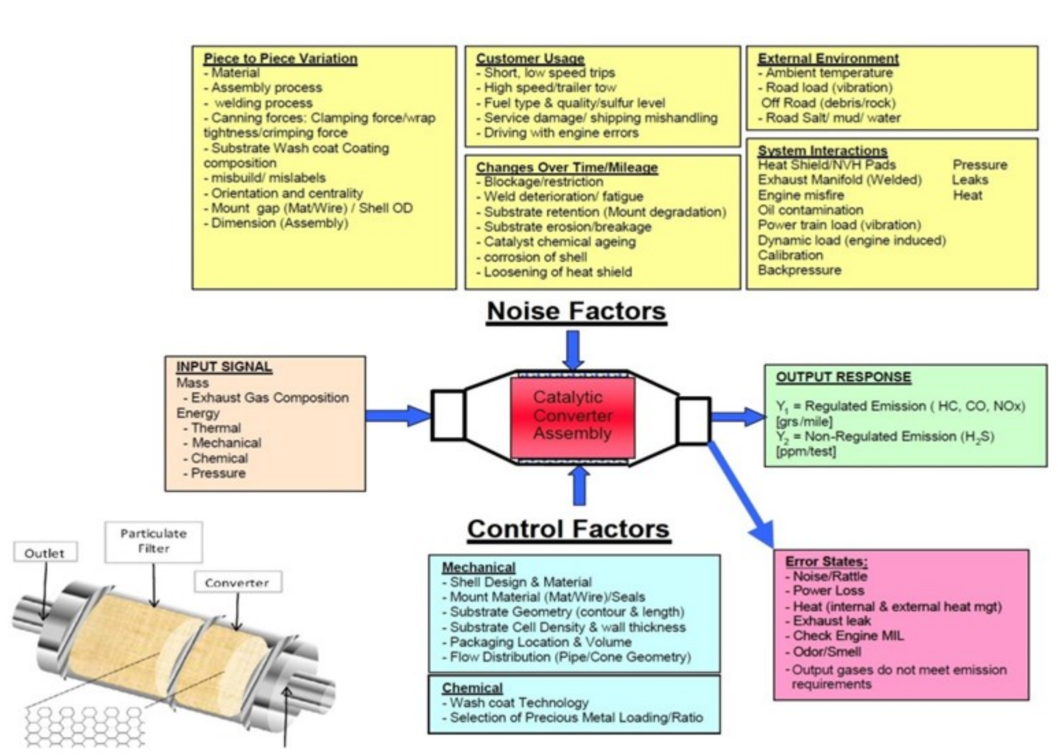
Abstract

The objective of this project is to predict product reliability in early design stages, including design conceptualization and embodiment. The prediction is based on information extracted from heterogeneous, multilevel sources such as previous components and products, expert opinions, early prototype testing, and initial simulations. The major approach is the development of a Bayesian framework that aggregates and processes the information and then quantitatively predicts product reliability in early design stages. Quantifying product reliability in early design stages helps reduce risk and avoid costly and unnecessary design changes. With a novel probabilistic graphical modeling approach, this project not only specifies the complex structure of the system reliability prediction but also integrates both subjective and objective information, thereby accommodating reliability-related data that are scattered, in different formats, at different levels of details, and from various sources. The accommodation of all the heterogeneous data allows for more accurate reliability prediction, leading to more effective actions identified early to prevent potential failures or reduce their likelihood.

Importance of estimating system reliability during early design stages

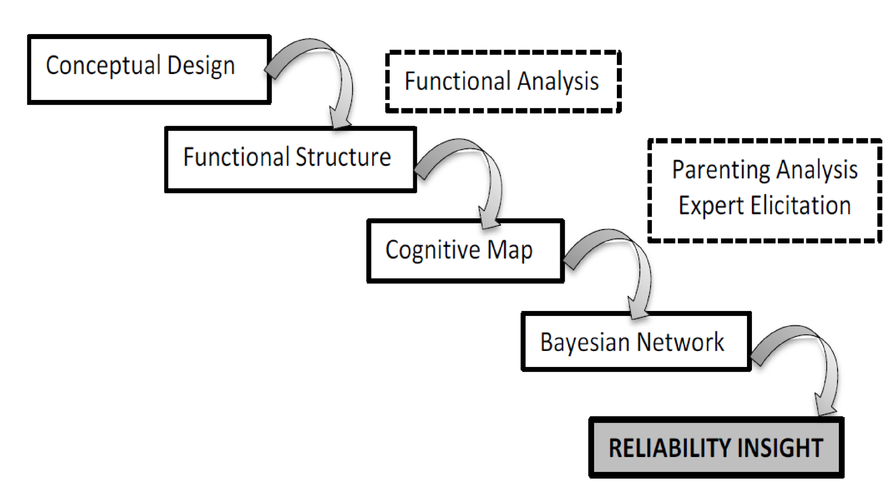
Reliability is the probability that a product performs its intended function under specified conditions during a specified period of time. In the past, reliability analysis had been primarily regarded as a passive term, i.e., an ad-hoc study of failures and failure time data of products, as a product's reliability could only be quantified after observing field failure data and/or life testing results. Nowadays, a proactive approach views reliability as a measure of impact on product performance improvement. This approach, demanded by the build-in reliability (BIR) philosophy, convenes reliability study as early as in the conceptual design stage. Performing reliability analysis earlier will not only



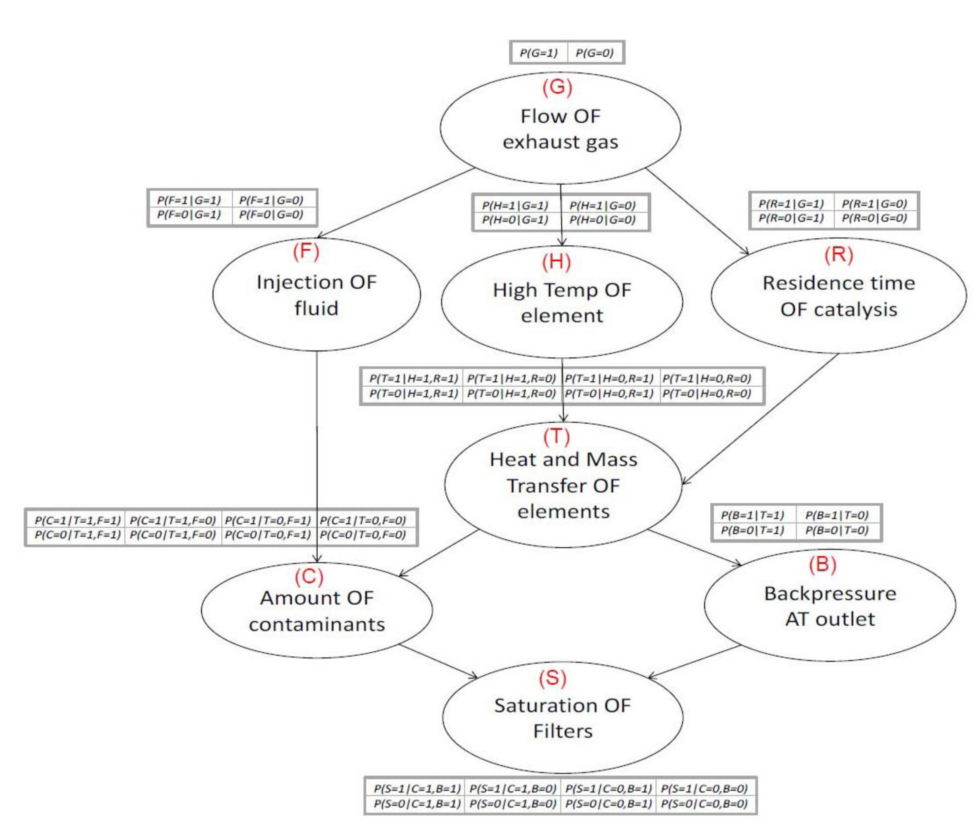
Heterogeneous reliability information from multiple sources

Source	Description	Method	Type	Uses
Customer demands	Customer's input leads eventually to the reliability requirement.	The methods such as market research and House of Quality can be used to transfer customer demands to reliability specifications	Subjective	Set reliability requirements.
Expert opinions	Experts have great insight on the risks that some components or design changes originate.	Various elicitation methods of expert opinions and failure modes and effects analysis (FMEA).	Subjective	Risk assessment for new designs.
Parent products	Parents have functional or structural similarities to new designs. They may share the same failure mechanism for the same function.	Retrieve the parent product's design data, test data and field failure data from existing reliability database.	Objective	Determine parent failure cause, failure modes, failure rates, etc.
Initial tests	Some material or component tests could provide crucial information.	Tests with limited scale.	Objective	Understand the performance of critical materials or components.
Simulations	Computer simulations of systems or subsystems can reveal how the system degrades over time.	Computer experiments	Objective	Provide an initial sense of system reliability.

Bayesian network models for conceptual designs



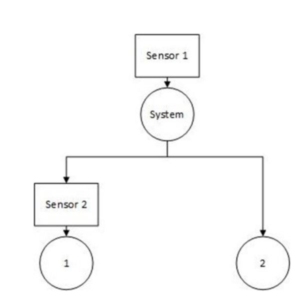
The methodology starts in the conceptual design phase, when a concept has been selected. Then, a functional analysis needs to be conducted. Using the function to failure approach, we define a failure when a function is not executed as expected. Following the methodology depicted by Augus-



Bayesian inference of reliability dependency

Bayesian network approach is proposed for evaluating the conditional probability of failure within a complex system, using a multilevel system configuration. Coupling with Bayesian inference, the posterior distributions of these conditional probabilities can be estimated by combining failure information and expert opinions at the component and system levels. Three data scenarios are considered in this study and they demonstrate that, with the quantification of the stochastic relationship of reliability within a system, the dependency structure in system reliability can be gradually revealed by the data collected at different system levels.

One big challenge in system reliability assessment is the lack of the complete lower-level data as presented in previous sections. A complex system does not necessarily have all components or subsystems being monitored at the same time. There can be a limited number of sensors deployed in the system to monitor the states of some components or subsystems, but not all of them.



State Vector # j	Node states $(x_1)_j$	$(x_2)_j$	$(x_0)_j$	State vector $\boldsymbol{x}_j$	Probability $Pr(\boldsymbol{x}_j \mid \boldsymbol{p})$
1	0	0	0	{0,0,0}	$(1-p_1)(1-p_2)(1-p_{00})$
2	0	0	1	{0,0,1}	$(1-p_1)(1-p_2)p_{00}$
3	0	1	0	{0,1,0}	$(1-p_1)p_2(1-p_{01})$
4	0	1	1	{0,1,1}	$(1-p_1)p_2 p_{01}$
5	1	0	0	{1,0,0}	$p_1(1-p_2)(1-p_{10})$
6	1	0	1	{1,0,1}	$p_1(1-p_2)p_{10}$
7	1	1	0	{1,1,0}	$p_1 p_2(1-p_{11})$
8	1	1	1	{1,1,1}	$p_1 p_2 p_{11}$

Our proposed Bayesian network model is coupled with Hierarchical Bayesian (HB) inference to enable model parameter estimation without explicitly specifying its prior distribution. We have developed a MATLAB program to perform a rapid compilation of the set of combinations of state vectors to be used in the MCMC simulation in WinBUGS.

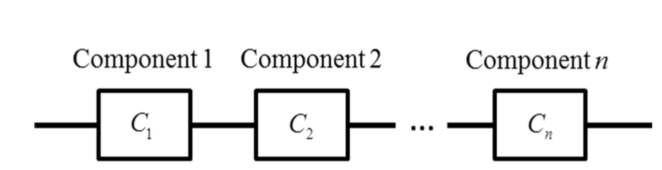
Product reliability prediction in early design stage

Background: It is not necessary to design all components for a new product. Existing components can be used.

Challenges: Component failures are dependent. Without considering the dependency, the system reliability prediction will be inaccurate, resulting in difficulties in decision making, such as selecting best design concepts with resect to reliability.

Existing method: For series systems, reliability bounds are

$$\prod_{i=1}^{n} R_i \le R_S \le \min\{R_i\}$$



The bounds may be too wide for decision making; the lower bound may be too conservative.

New method: Use a physics-based approach to produce much narrower system reliability bounds.

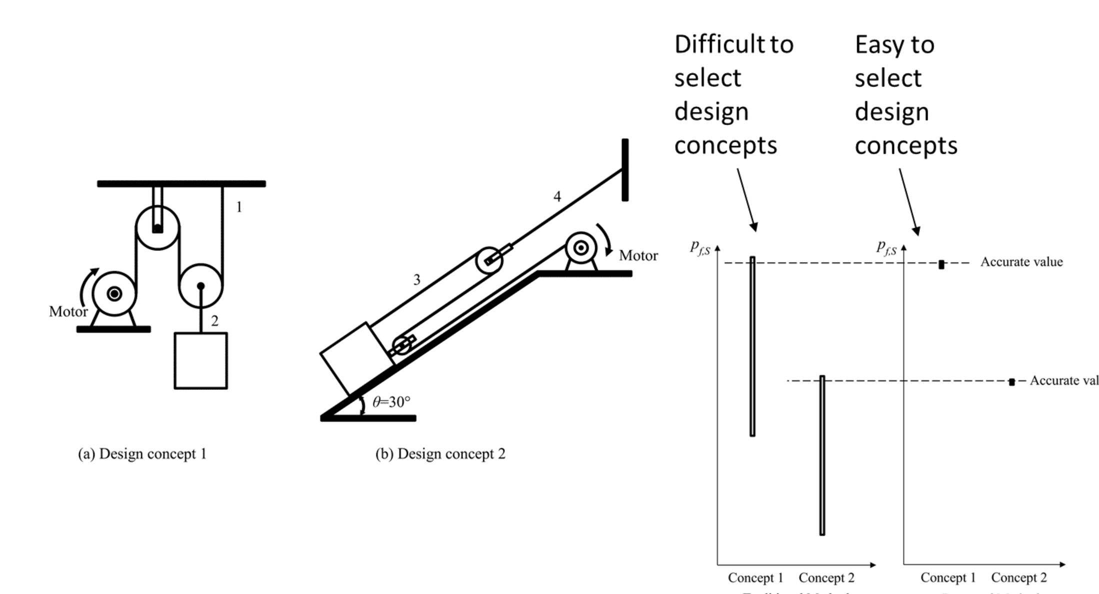
Information required for system designers:

- Component reliabilities
- Distribution of the system load
- Estimated range of factors of safety of component designs

Model: Use optimization

- Objective: System reliability (min and max)
- Design variables: unknowns of component designs, such as distribution parameters of component strengths
- Constraints: component reliabilities, estimated range of component factors of safety, and others.

Example: Two design concepts for a hoisting devise; design concept two is better than design concept one.



Conclusions:

- It is possible to use a physics-based approach to predict system reliability more accurately.
- Narrow system reliability bounds better assist design decisions.

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