Complexity Management in the Industry

August 14th, 2008

Agenda

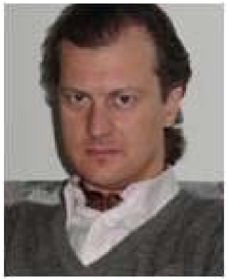
Complexity Management in the Industry

August 14th, 2008

8am PDT (Los Angeles) / 11am EDT (New York) / 5pm CET (Paris)

- Welcome & Introduction (Overview of NAFEMS Activities)
  - Matthew Ladzinski, *NAFEMS North America*
- Complexity Management in the Industry
  - Dr. Jacek Marczyk, *Ontonix*
- Q&A Session
  - Panel
- Closing

Ladzinski



Marczyk

THE INTERNATIONAL ASSOCIATION FOR THE ENGINEERING ANALYSIS COMMUNITY

An Overview of NAFEMS NA Activities

Matthew Ladzinski
NAFEMS
North American Representative

Planned Activities in North America

➢ Webinars

- New topic each month!

- Recent webinars:
  - Multiphysics Simulation using Implicit Sequential Coupling
  - CCOPPS: Fatigue of Welded Pressure Vessels
  - Applied Element Method as a Practical Tool for Progressive Collapse Analysis of Structures
  - AUTOSIM: The Future of Simulation in the Automotive Industry
  - A Common Sense Approach to Stress Analysis and Finite Element Modeling
  - The Interfacing of FEA with Pressure Vessel Design Codes (CCOPPS Project)
  - Multiphysics Simulation using Directly Coupled-Field Element Technology
  - Methods and Technology for the Analysis of Composite Materials
  - Simulation Process Management
  - Simulation-supported Decision Making (Stochastics)
  - Simulation Driven Design (SDD) Findings

To register for upcoming webinars, or to view a past webinar, please visit: www.nafems.org/events/webinars

Planned Activities in North America

NAFEMS NA 2008 Regional Summit

NAFEMS 2020 Vision of Engineering Analysis and Simulation

- ***NAFEMS 2020*** will bring together the leading visionaries, developers, and practitioners of CAE-related technologies and business processes
- Goal: Provide attendees with the best "food for thought and action" to deploy CAE over the next several years
- Location: Hampton Roads Convention Center,
  Hampton, Virginia
- Date: October 29-31, 2008

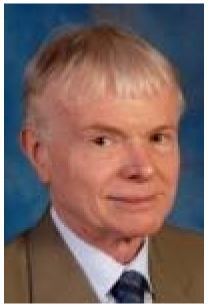
Agenda Now Available

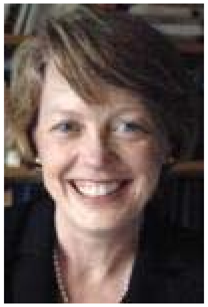
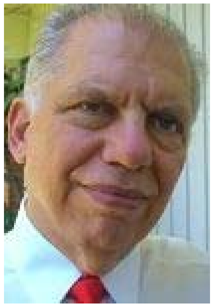
For more information, visit:

www.nafems.org/nafems2020

Keynote Presenters for NAFEMS 2020

- **Prof. Ahmed Noor**, *Old Dominion University*
- **Prof. Thomas J.R. Hughes**, *University of Texas at Austin*
- **Dr. Takeshi Abe**, *Ford Motor Company*
- **Prof. Mary Boyce**, *MIT*
- **Dr. Joel Orr**, *Cyon Research*

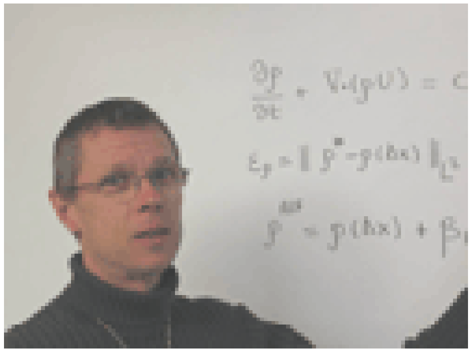
2-Day Short Course on V&V for Aerospace, Civil and Mechanical Engineers

Finite Element Model Validation, Updating, and Uncertainty Quantification for Linear and Non-linear Models

• **Goal**: Attendees will learn the latest techniques for evaluating the accuracy of computational models over a range of parameter values, how to design validation experiments that will determine the simulation range of validity, and how to calibrate model parameters to reflect the measured response from experiments – event for nonlinear Models

•**Location**: Hampton Roads Convention Center
Hampton, Virginia

•**Date**: October 27-28, 2008



For more information, visit: www.nafems.org/nafems2020

NAFEMS

Complexity Management in The Industry

Ontonix

NAFEMS Webinar, 14-th August, 2008

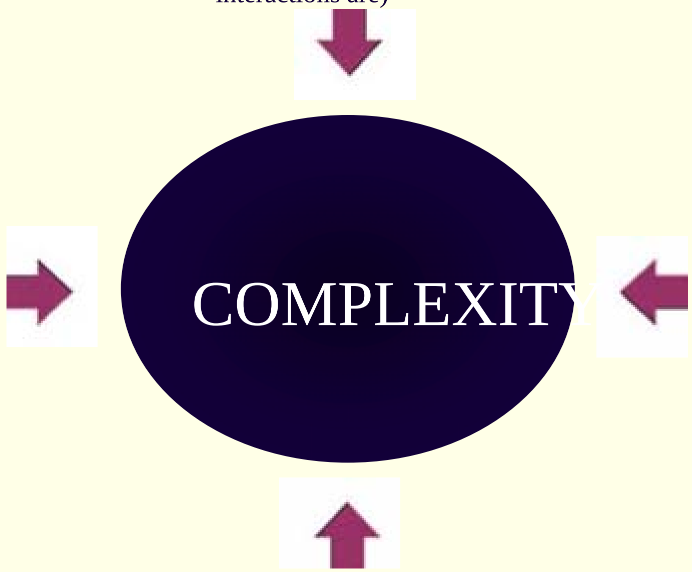
What is Complexity?

- Complexity is an attribute which characterizes every system, just like energy or momentum. It can be measured, and therefore managed. The value ranges from 0 to infinity.
- Every dynamical system possesses a maximum sustainable level of complexity. Close to this maximum, called critical complexity, the system becomes fragile and vulnerable.
- Critically complex systems are very difficult to manage and can easily develop surprising behavior.
- The risk exposure of any dynamical system can be measured and understood in an innovative way via complexity.
- Based on the concepts of complexity and critical complexity, new ways of measuring robustness have been conceived.

What is Complexity?

Complexity is a function of structure, uncertainty, coarse-graining
and resolution

Uncertainty
(How noisy the interactions are)



Structure
(How information flows within a given system)

Resolution
(How much precision is required)

Coarse-graining
(How many variables are needed to describe a problem)

Complex or Complicated?

- A system may be complicated, but still have low complexity.
- A large number of parts doesn't generally imply high complexity. It does, in general, imply a complicated system.
- In order to measure the amount of complexity it is necessary to take uncertainty into account.
- Complexity implies capacity to surprise, to deliver unexpected behaviour.
- Deterministic systems have 0 complexity.

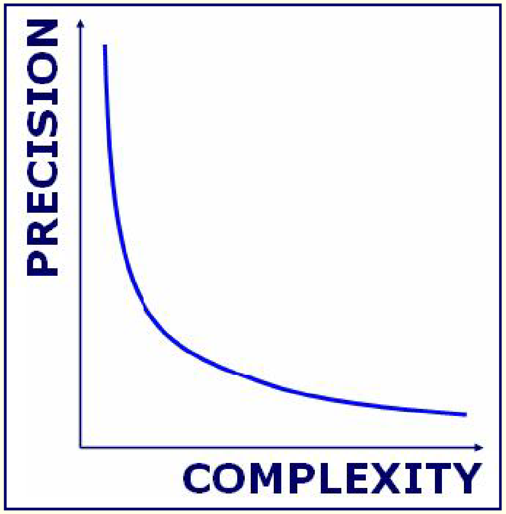
Complexity Principles

- Principle of Complexity:

  When the complexity and uncertainty of an engineering system increase, our ability to predict its behavior diminishes until a threshold is reached beyond which accuracy and significance become almost mutually exclusive.

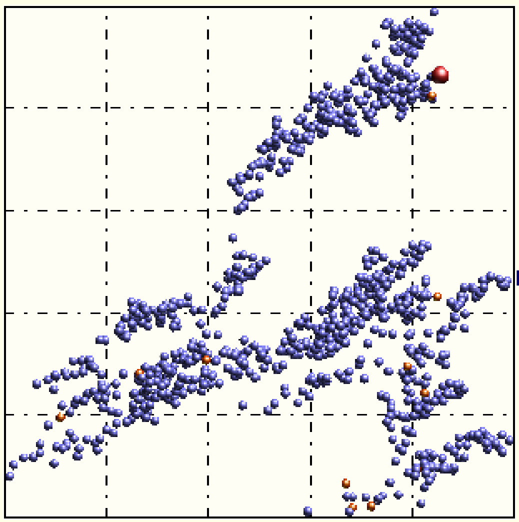
- Principle of Incompatibility:

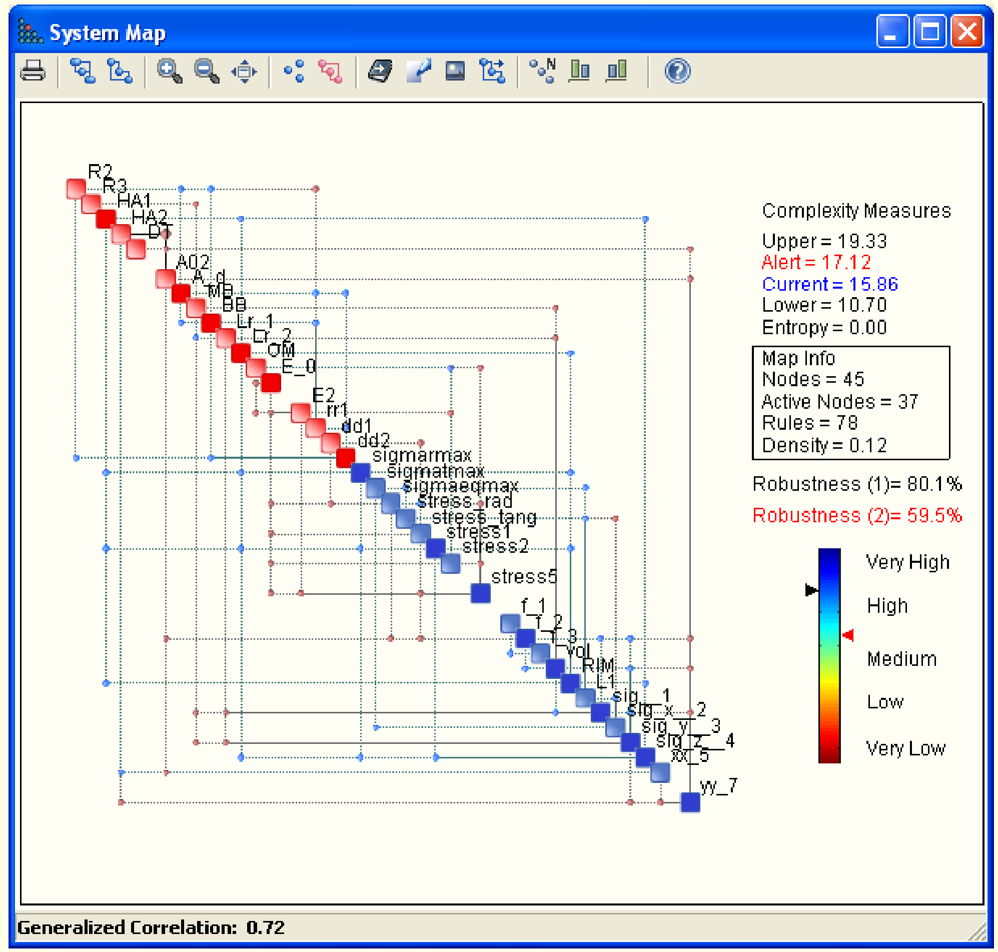
  High precision is incompatible with high complexity.



L. Zadeh, UCLA

Extracting Knowledge From Data





We transform multi-dimensional data to Process Maps using our proprietary image-processing technology.

How OntoSpace Generates Maps

OntoSpace builds maps based on raw User data. These are known as System Maps. The significant relationships between the nodes are established automatically. In other words, the User does not have to define in any way how the nodes of the graph are linked – this is done by OntoSpace using a proprietary algorithm.

	Variable 1	Variable 2	Variable 3	Variable 4	Variable 5	Variable 6	Variable 7	Variable 8	Variable 9	Variable 10	Variable 11	Variable 12	
measurement 1	2.7202888e+003	7.4722596e+001	3.3732330e+001	1.0184837e+002	9.0967402e+001	1.3025740e+000	5.8491109e+002	2.0883948e+003	5.7746246e+002	2.0745664e+003	7.7027814e+001	4.7343477e+001	9.32126
measurement 2	2.7202888e+003	7.4722596e+001	3.3732330e+001	1.0184837e+002	9.0967402e+001	1.3025740e+000	5.8491109e+002	2.0883948e+003	5.7746246e+002	2.0745664e+003	7.7027814e+001	4.7343477e+001	9.32126
measurement 3	2.7472810e+003	7.5254340e+001	3.2769872e+001	9.9563658e+001	9.0359902e+001	1.2958549e+000	5.7800692e+002	2.1200529e+003	5.7044970e+002	2.1071991e+003	7.7609260e+001	4.4859857e+001	9.25134
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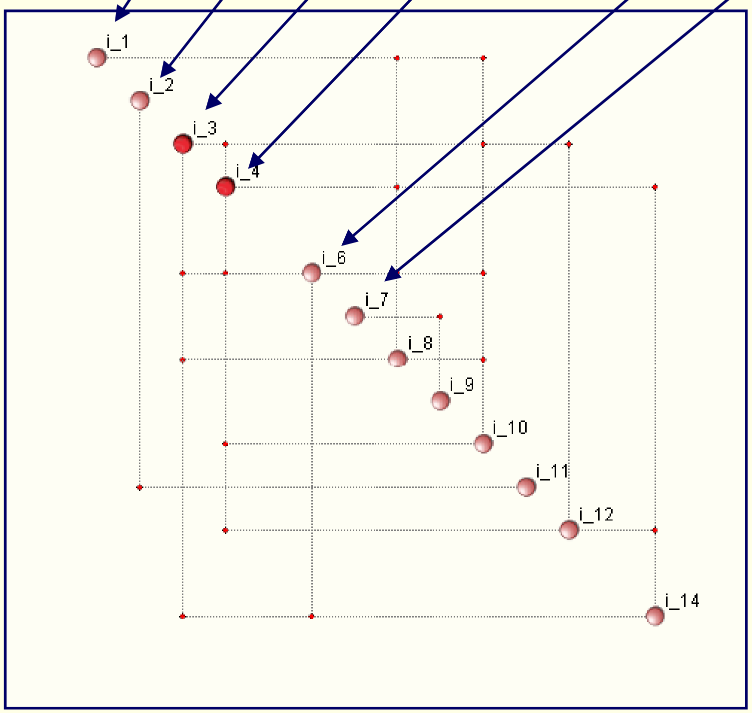
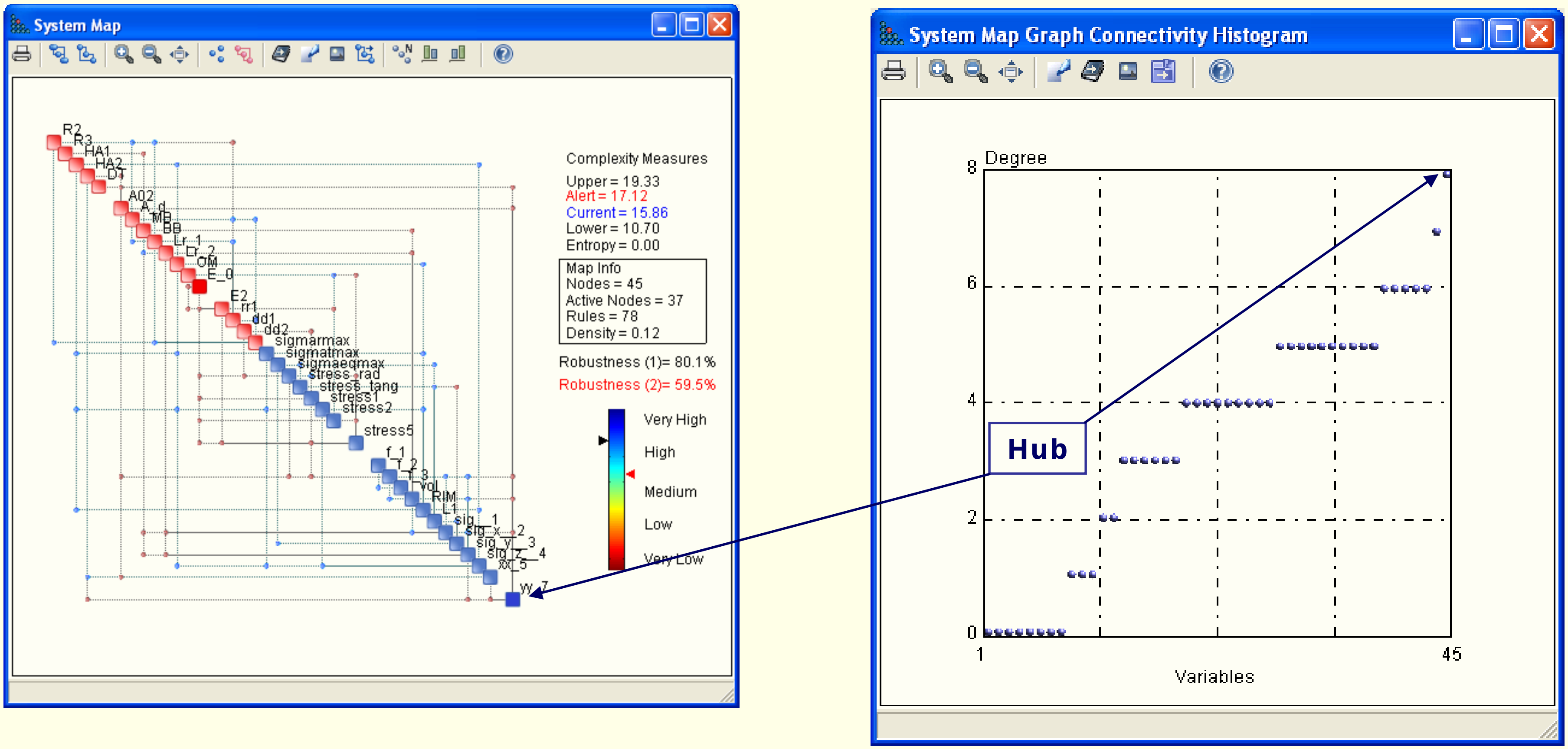
measurement 498	2.6963742e+003	7.4267584e+001	3.2300819e+001	9.9709857e+001	9.0880438e+001	1.2846033e+000	6.0231885e+002	2.0989936e+003	5.9500231e+002	2.0844376e+003	7.6470372e+001	4.7246972e+001	9.24455
measurement 499	2.7161385e+003	7.4648496e+001	3.1284797e+001	9.7180980e+001	8.9747118e+001	1.2855390e+000	5.7932586e+002	2.1128403e+003	5.7174746e+002	2.1006561e+003	7.7008998e+001	4.2349411e+001	9.30133
measurement 500	2.6995332e+003	7.5451365e+001	3.4156452e+001	1.0258146e+002	9.0543986e+001	1.3110797e+000	5.7014063e+002	2.0590153e+003	5.6257964e+002	2.0467060e+003	7.7843365e+001	4.4955206e+001	9.21655



In the example on the left, one may notice that variable 5 (node 5) isn't linked to any other node. This is because OntoSpace has determined that there are no significant relationships between this variable and all the remaining variables in the system.

Process Map Topology: Understanding Dynamical Systems



The concept of hub is fundamental for the analysis of system robustness. Single-hub systems are known to be more vulnerable than multi-hub systems. Loss of a hub in a single-hub system may lead to catastrophic collapse.

Complexity x Uncertainty = Fragility

- When uncertainty meets high complexity, the result is fragility. Simple systems can cope better with uncertainty than highly complex systems.
- Highly complex systems are more exposed to the effects of uncertainty because of the countless ways in which they process information. They can fail in many ways, often due to apparently innocent causes.
- Uncertainty in the environment, cannot be avoided. We must learn to live with it. Hence the need to manage complexity.
- Since fragility is the prelude to risk, risk management can be accomplished via complexity management.

Nature Increases Complexity (Functionality): There is a Price to Pay!

Complexity x Uncertainty = Fragility

$$\mathbf{C}_{\text{design}} \,\mathbf{X}\, (\mathbf{U}_{\text{manufacturing}} + \mathbf{U}_{\text{environment}}) = \mathbf{F}_{\text{product}}$$

- A highly sophisticated design will result in a fragile product if:
  - The manufacturing process is of poor quality
  - The environment is very “turbulent”

- Hence, a more robust product requires:
  - A high-quality manufacturing process, or
  - A less severe environment in which to function, or
  - A less “ambitious” initial design

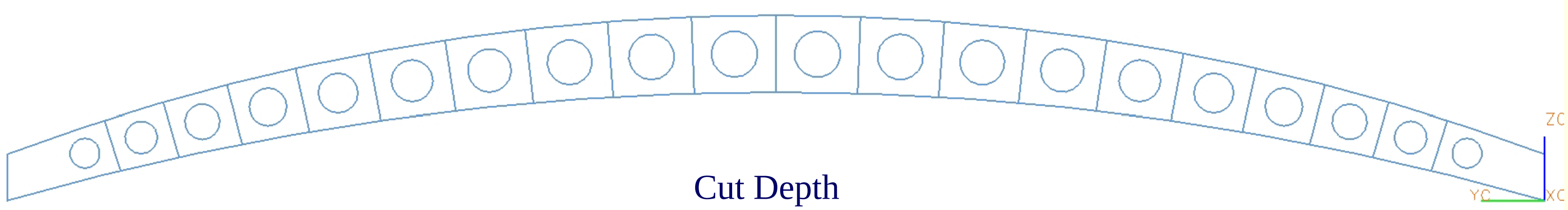
Complexity-Based Design

A less complex solution is generally:

- Less expensive to design and engineer
- Less expensive to manufacture
- Less expensive to service (replace broken components, etc.)
- Cheaper
- Easier to operate
- Less fragile. This means:
  - Less warranty costs
  - Less recalls
  - Less law-suits

Complexity-Based Computer-Aided Design: Pedestrian Bridge

Design parameters:



Complexity-Based CAD: Pedestrian Bridge Geometric parameters

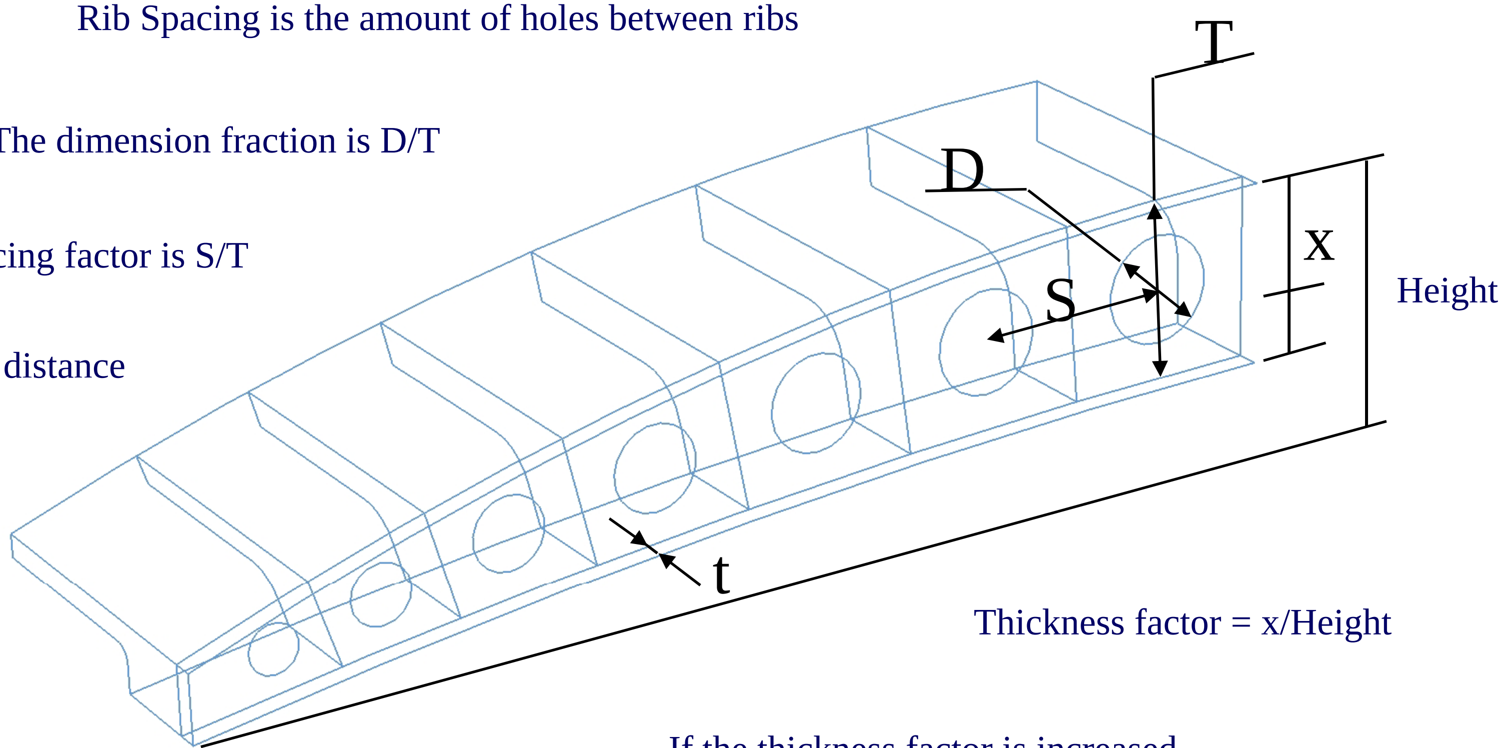
Quarter model view:

Rib Spacing is the amount of holes between ribs

The dimension fraction is D/T

The spacing factor is S/T

t is the flange distance



Thickness factor = x/Height

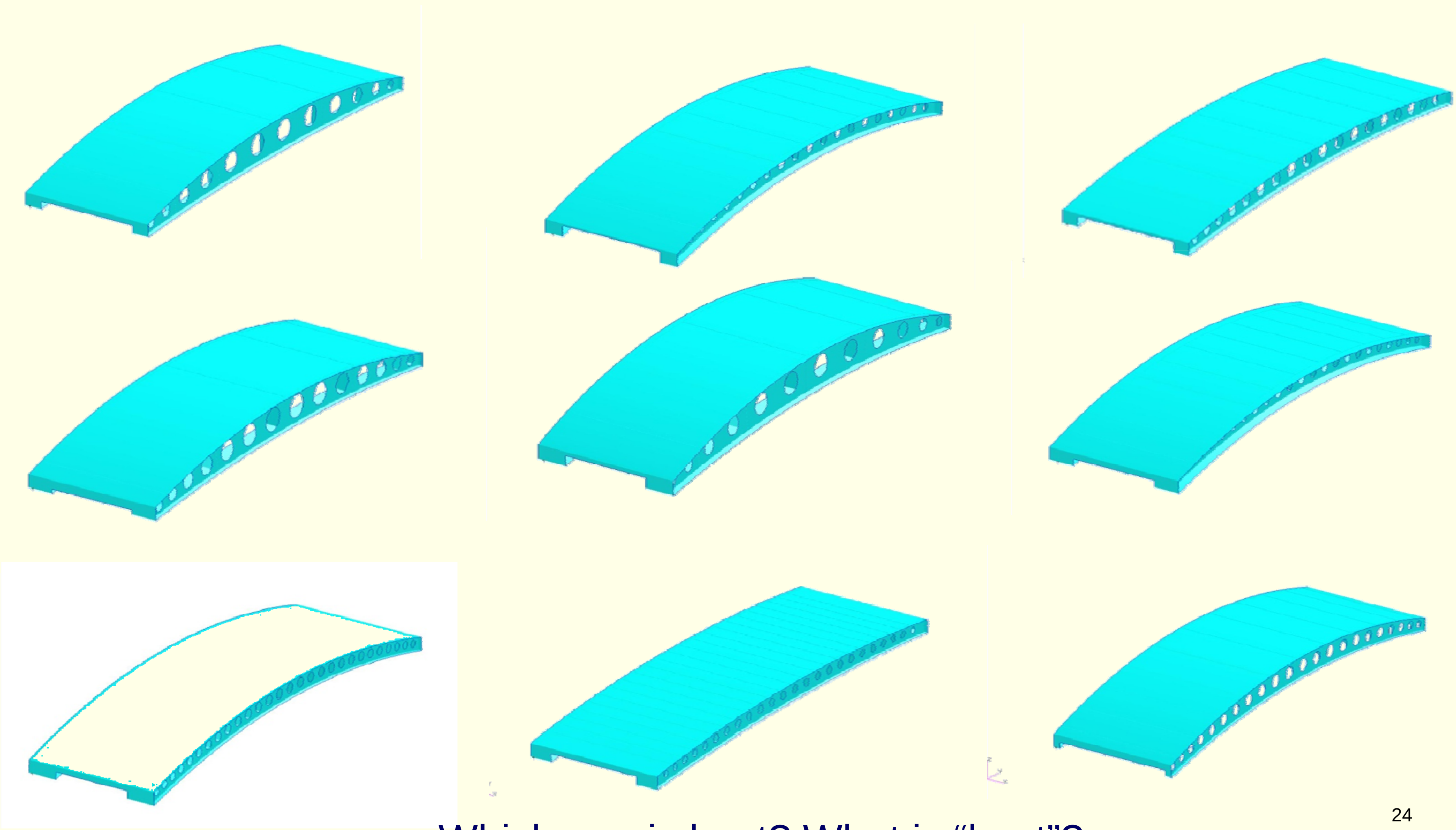
If the thickness factor is increased

Cut depth, width and radius determine the shape of the ribs

Complexity-Based CAD – The Concept

- Starting from the initial nominal model, a sequence of randomly generated solutions is created. This is done using Monte Carlo techniques and a multi-run environment.
- For every solution, a CAD system is used to automatically generate an FE mesh.
- For every mesh a static and an eignevalue analysis is run in order to determine stresses, deflections and natural frequencies.
- The process is repeated a few hundred times and is fully automatic (one loop).
- The results are processed and feasible solutions are determined by specifying desired levels of:
  - Stresses
  - Deflections
  - Natural frequencies
- Various solutions are found to satisfy constraints and performance objectives.

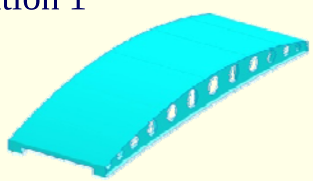
Complexity-Based CAD – The Concept

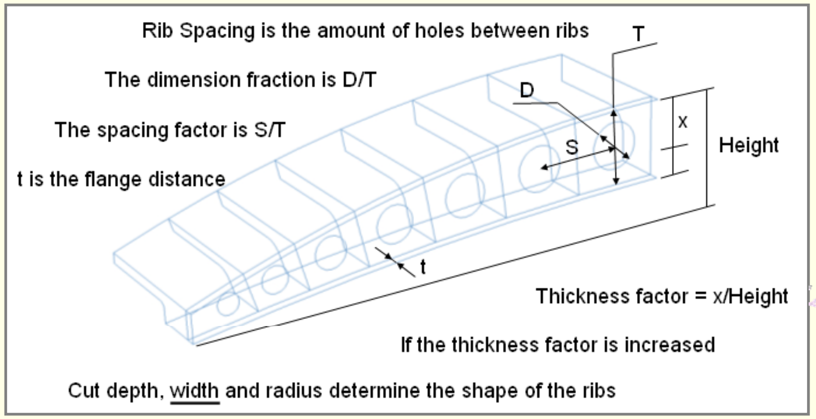


Which one is best? What is "best"?

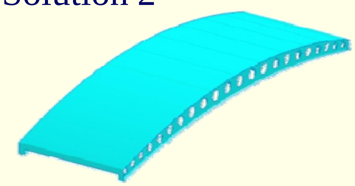
Complexity-Based CAD – The Concept

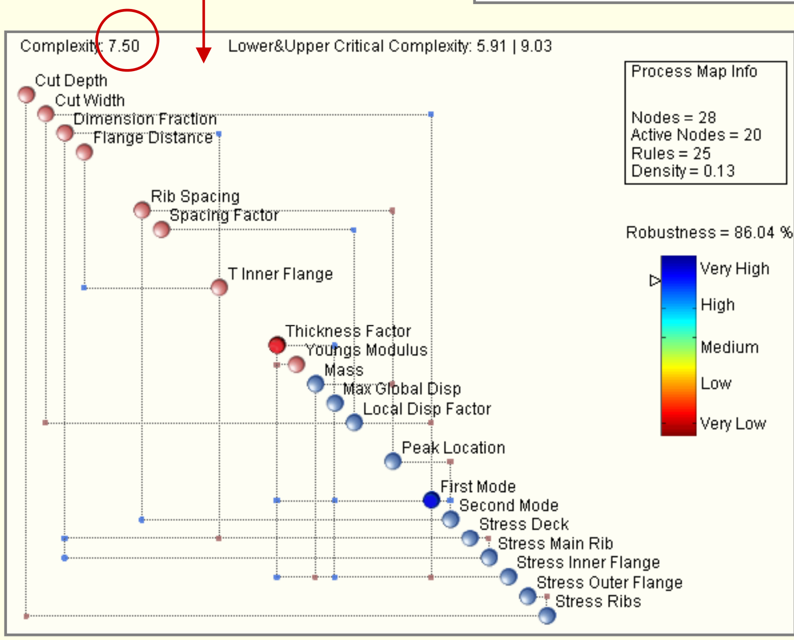
Solution 1

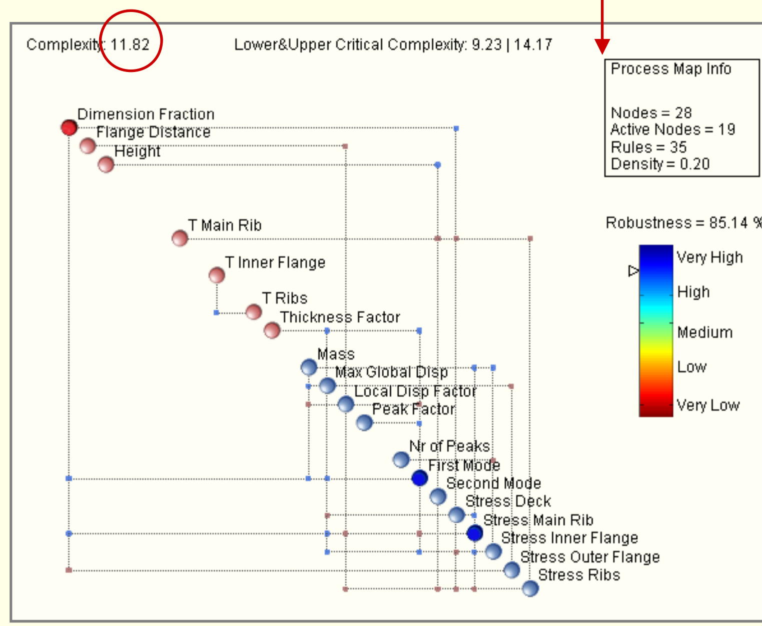




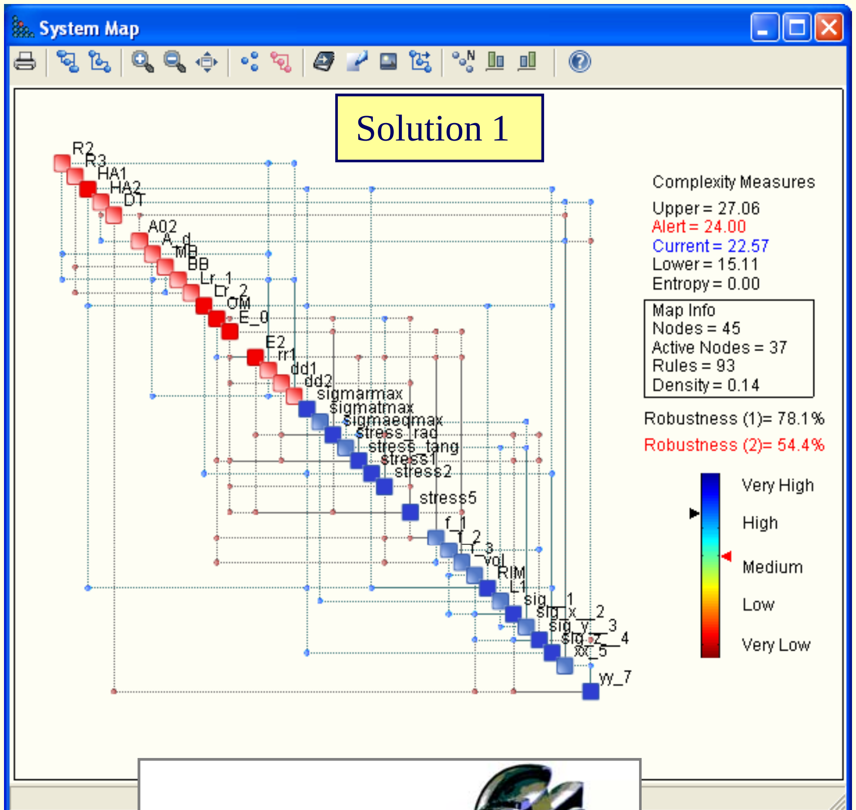
Solution 2

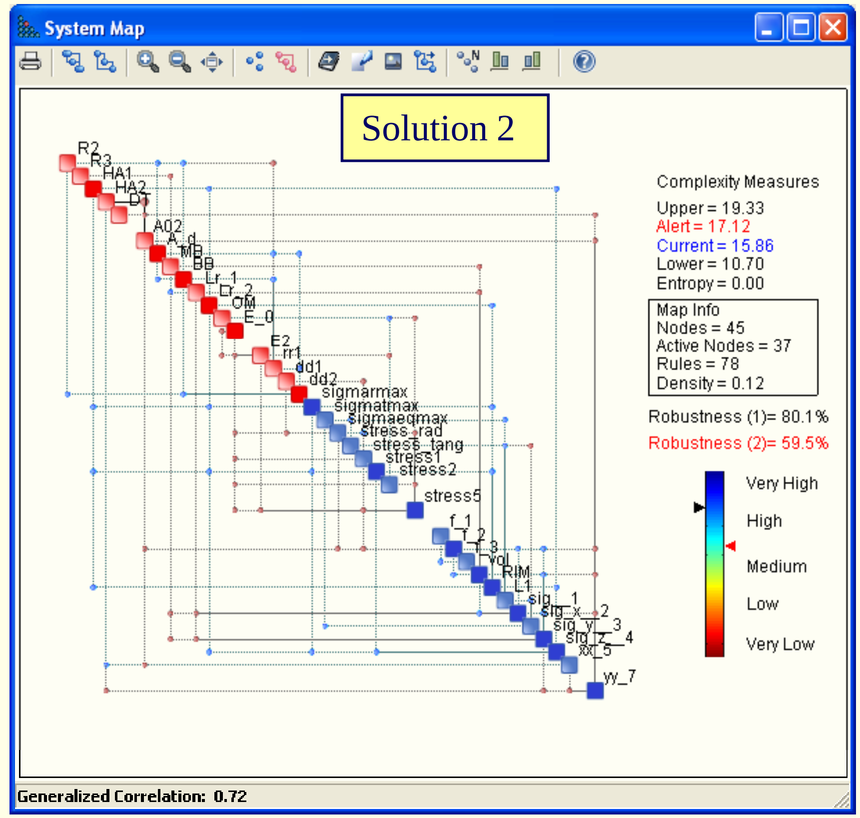


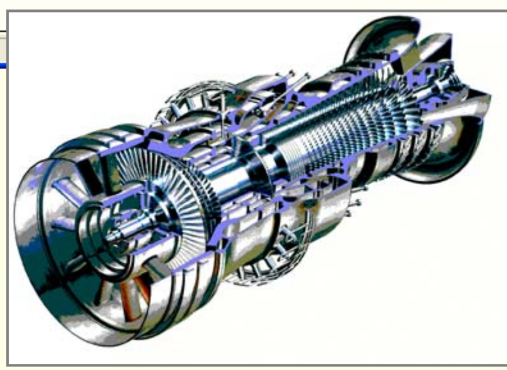




Example of Complexity-Based Design: Turbine Disk Design





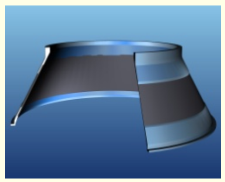


Solution 2 has much lower complexity (15.8 vs. 22.6) and slightly higher robustness than Solution 1.

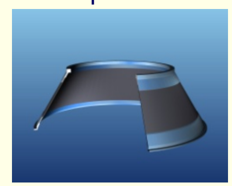
Example of Complexity-Based Design: The James Webb Space Telescope

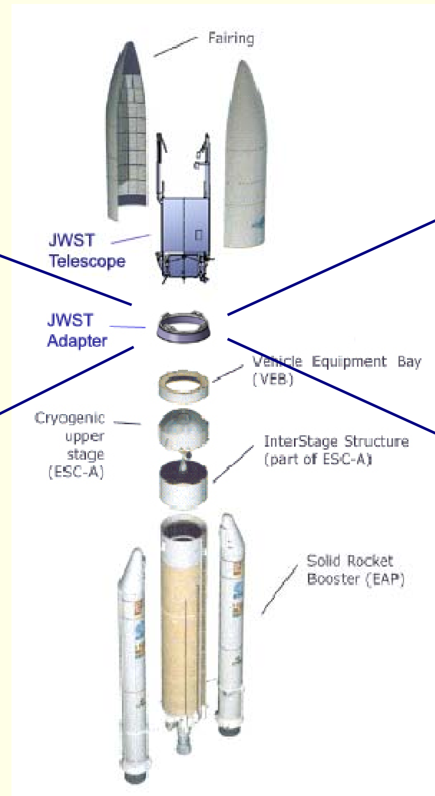
Best option: lowest complexity with same performance

Option 1



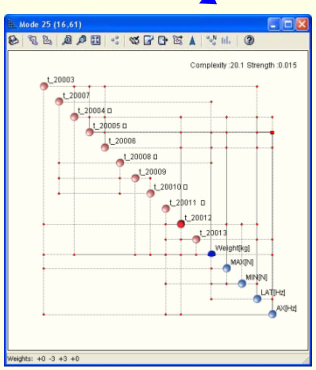
Option 2

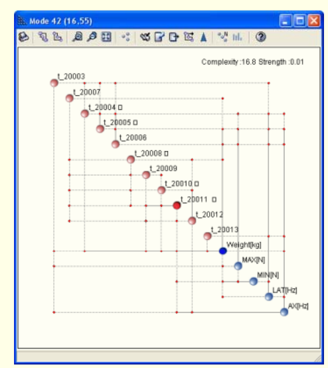




Option 3

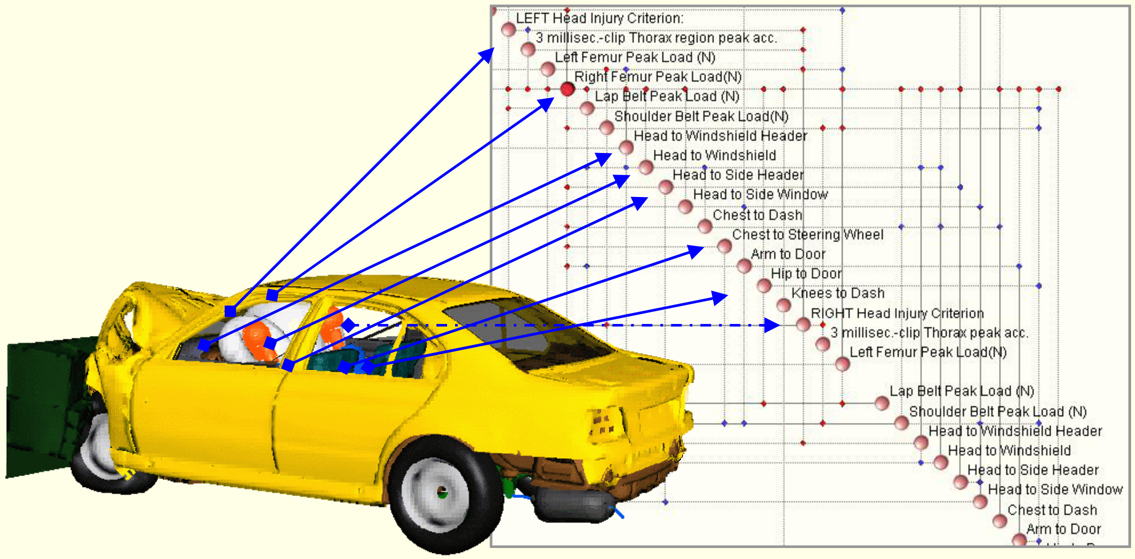
Option 4

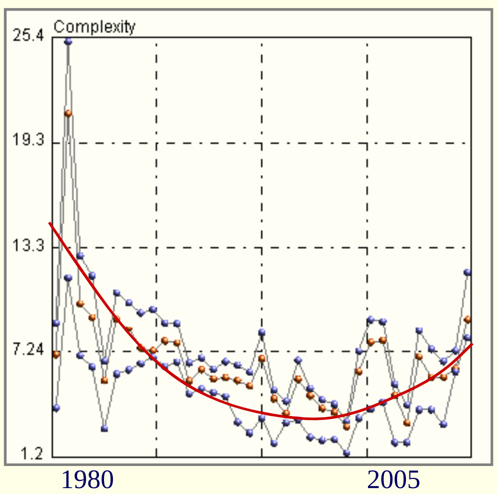


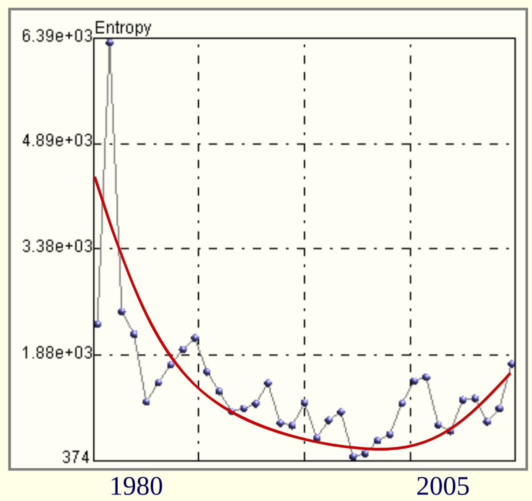


James Webb Space Telescope payload adapter.
Courtesy EADS CASA Espacio.

Crash Test Data Processing

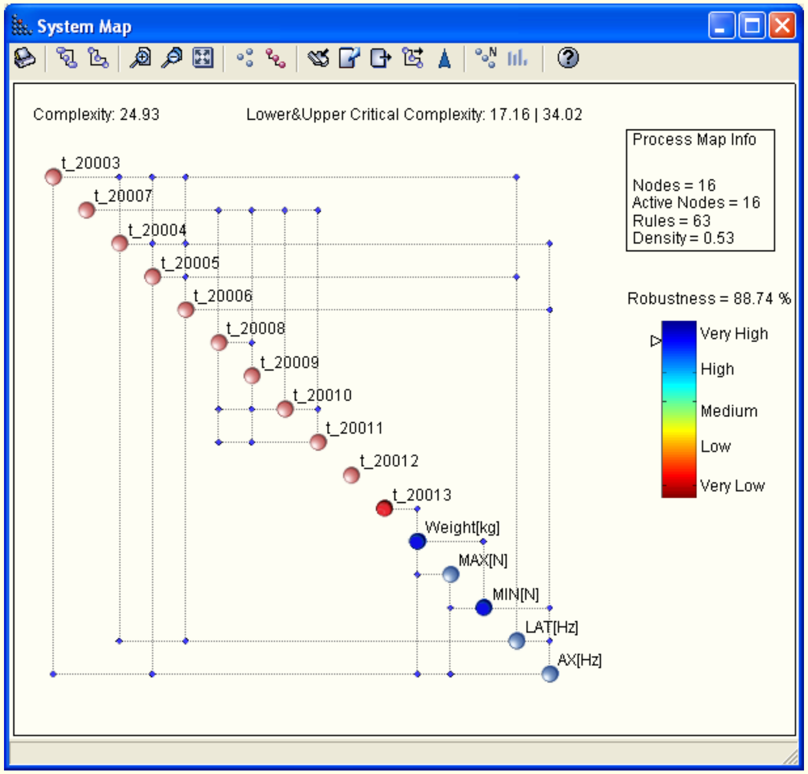


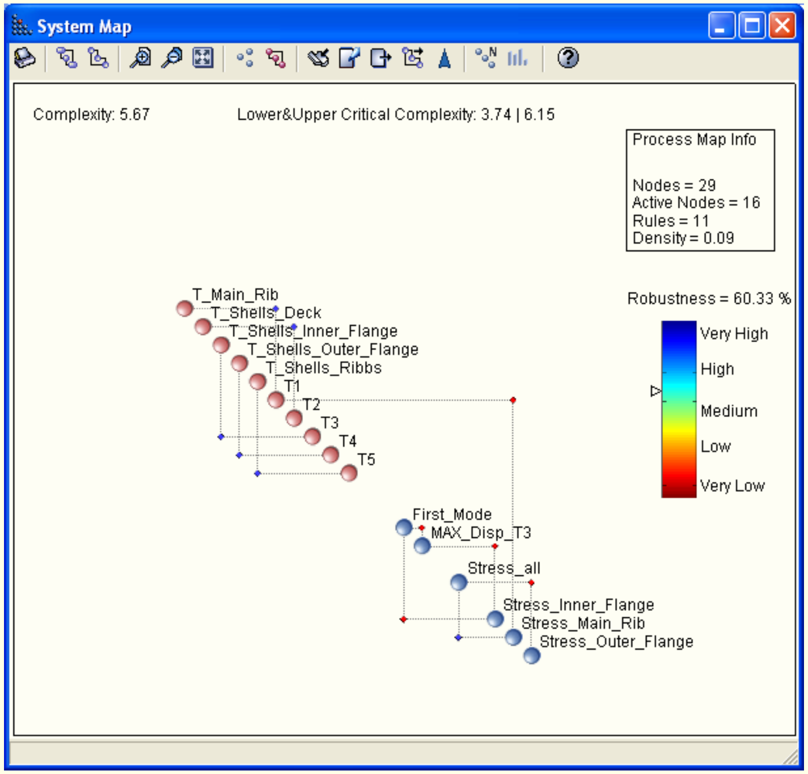




Analysis of crash-test data shows that over the past decade, complexity has been increasing.

Measuring Robustness in Mechanical Systems



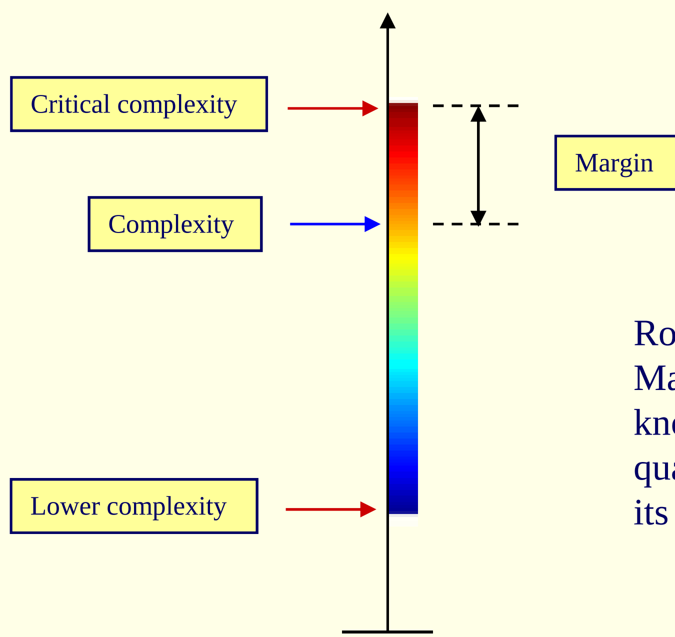


Robust design and related techniques have been object of discussion for over a decade. However, the robustness of designs conceived using such methods has never actually been measured and no global measure of robustness has ever been proposed.

Recently developed complexity-based robustness measures allow engineers to quantify the global robustness of any dynamical system.

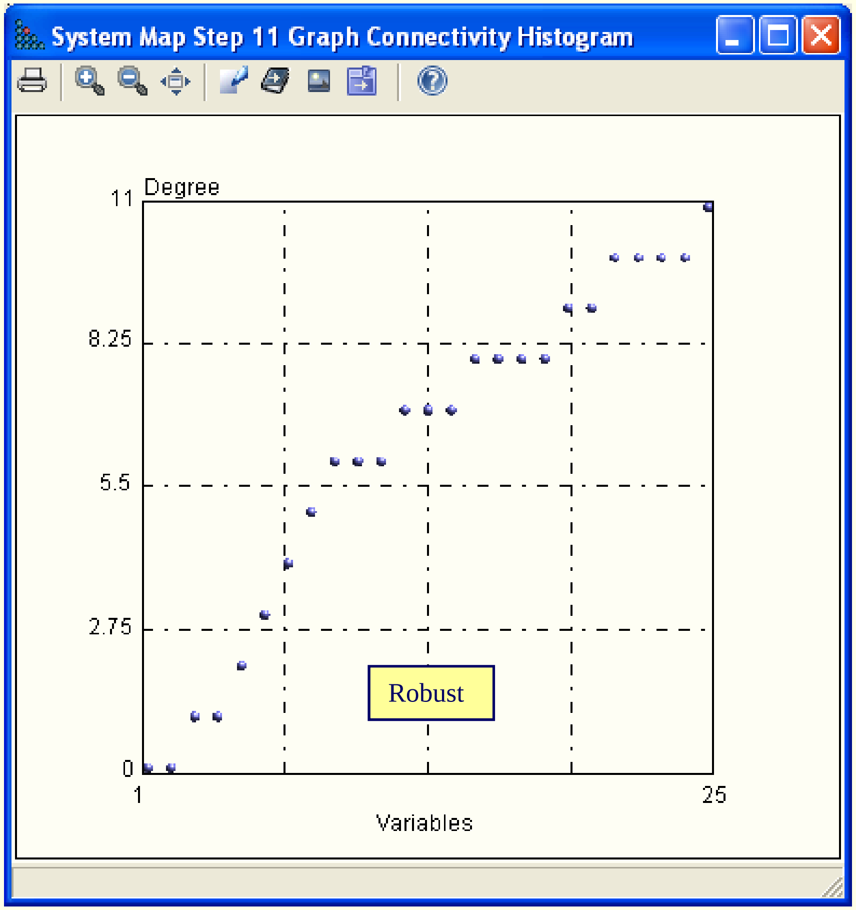
Measuring Robustness in Dynamical Systems

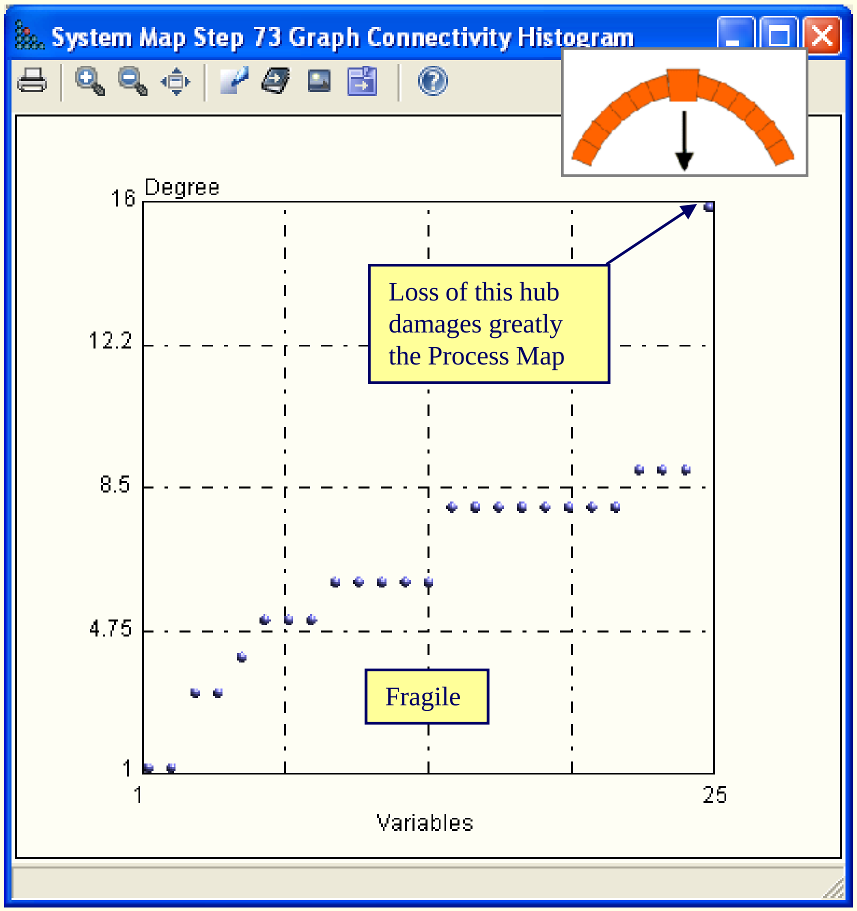
- A fundamental concept is that of critical complexity.
- In the proximity of critical complexity a Process Map begins to break up.
- The topology of the Process Map reflects the functionality of a given system in that it reflects the structure of information flow within the system.
- It is crucial to maintain the topology of a Process Map intact for a correctly funtioning system.



Robustness is proportional to the Margin $\mathbf{C}_{critical} - \mathbf{C}$. This measure is known as topological robustness and quantifies the system's ability to preserve its functionality.

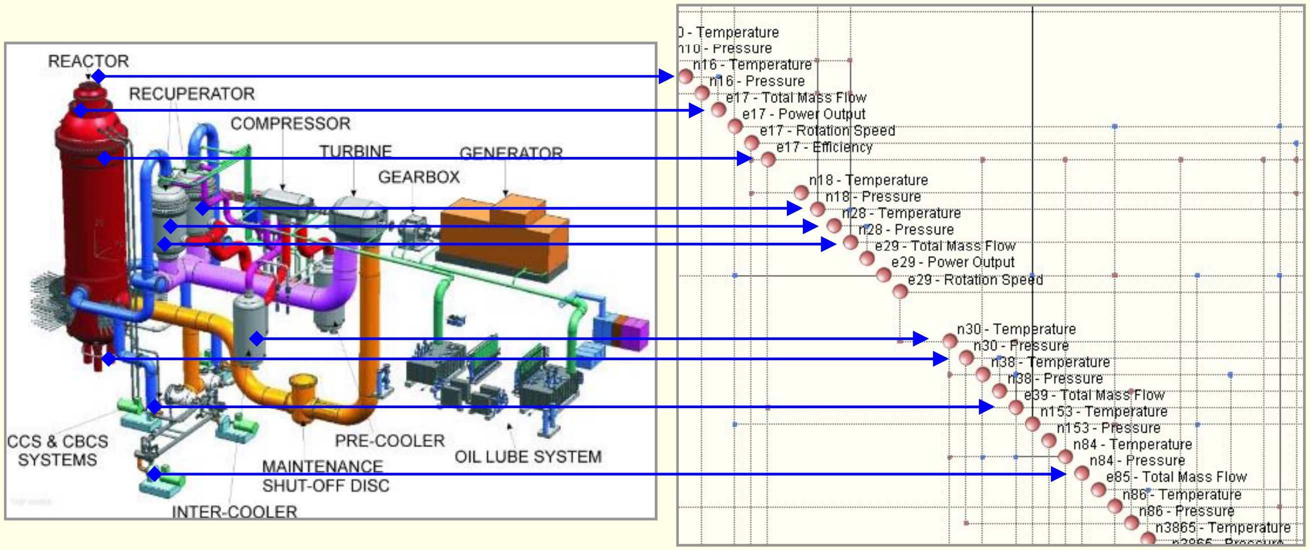
More on Robustness: The Connectivity Histogram



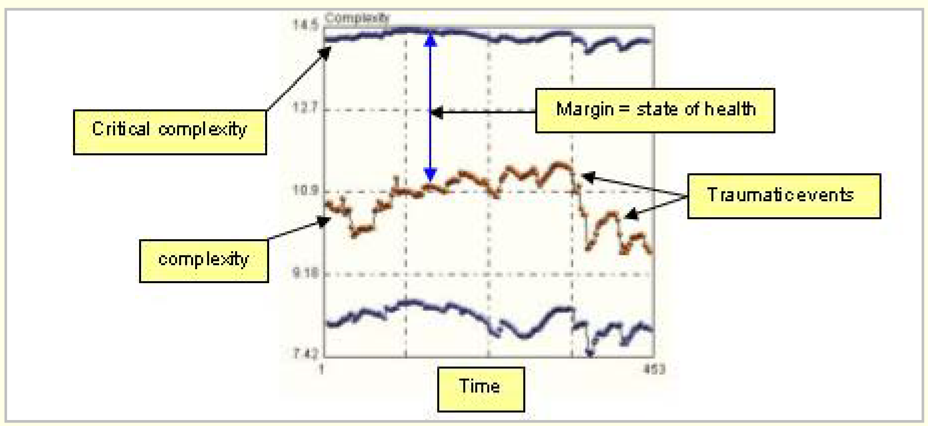


Additional information on robustness may be obtained examining the shape of the Connectivity Histogram. Spiky histograms (known as Zipfian) denote fragile topologies, while flatter ones point to more robust systems.

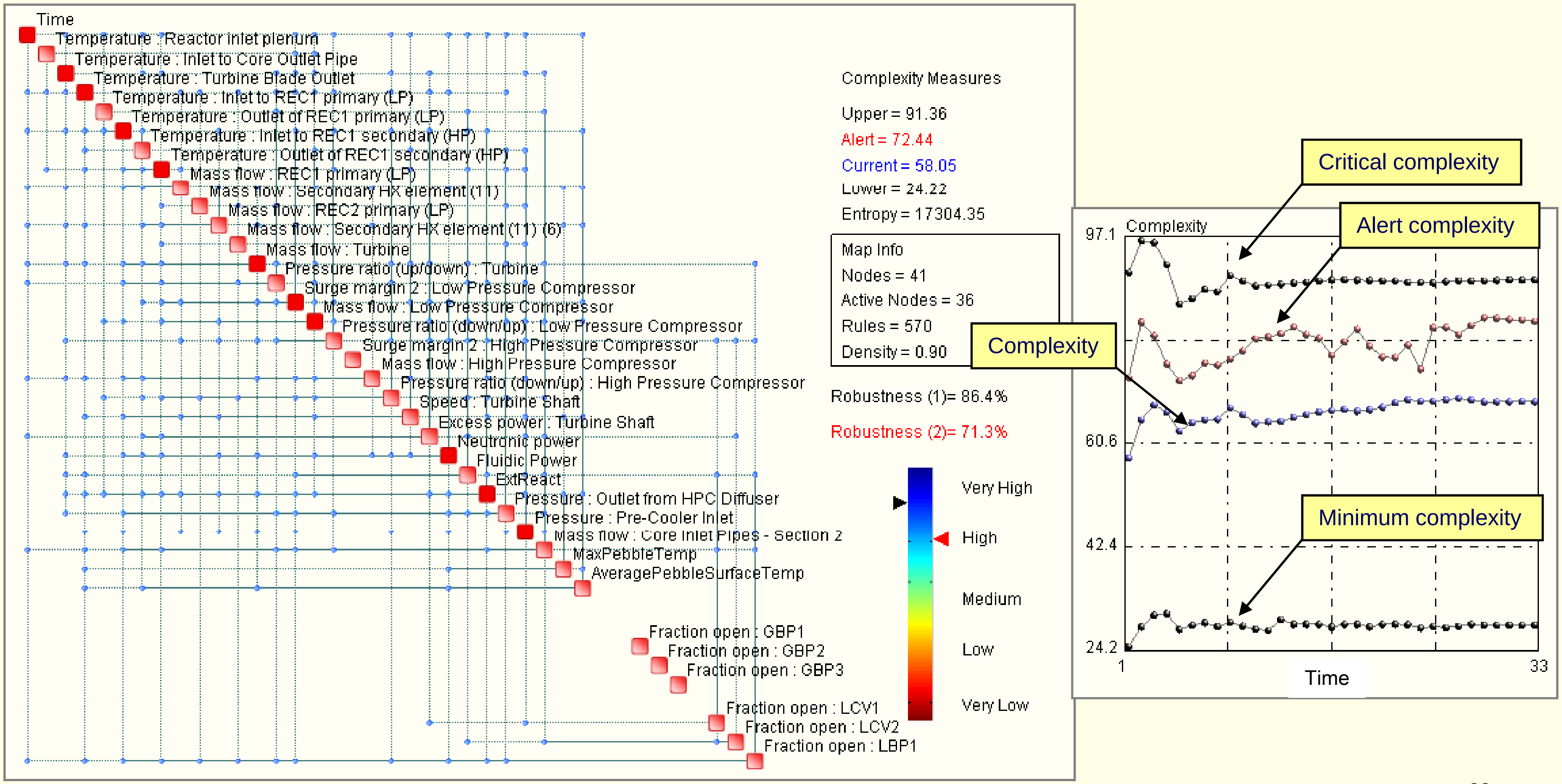
Holistic Plant Monitoring



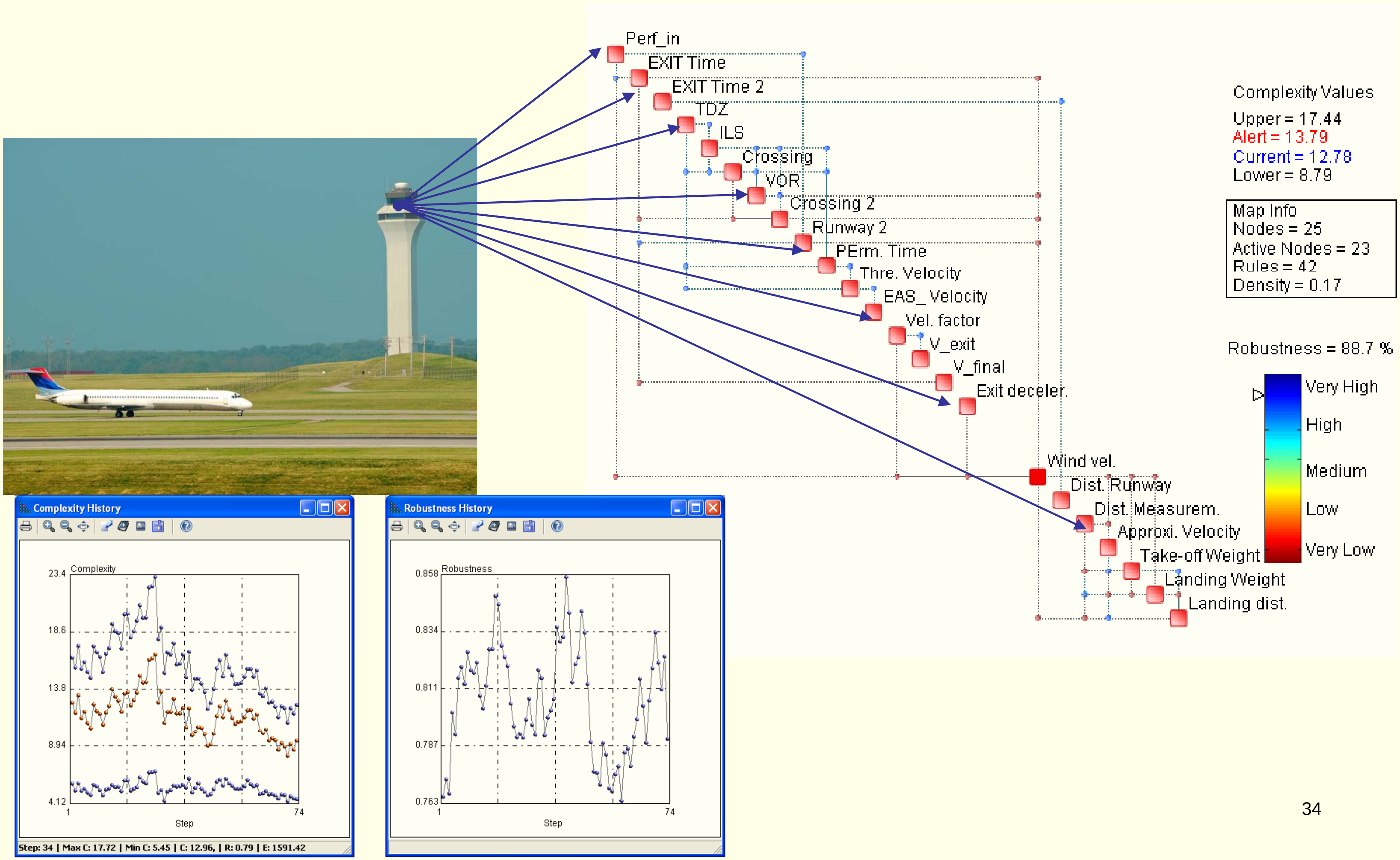
Courtesy, PBMR Ltd.



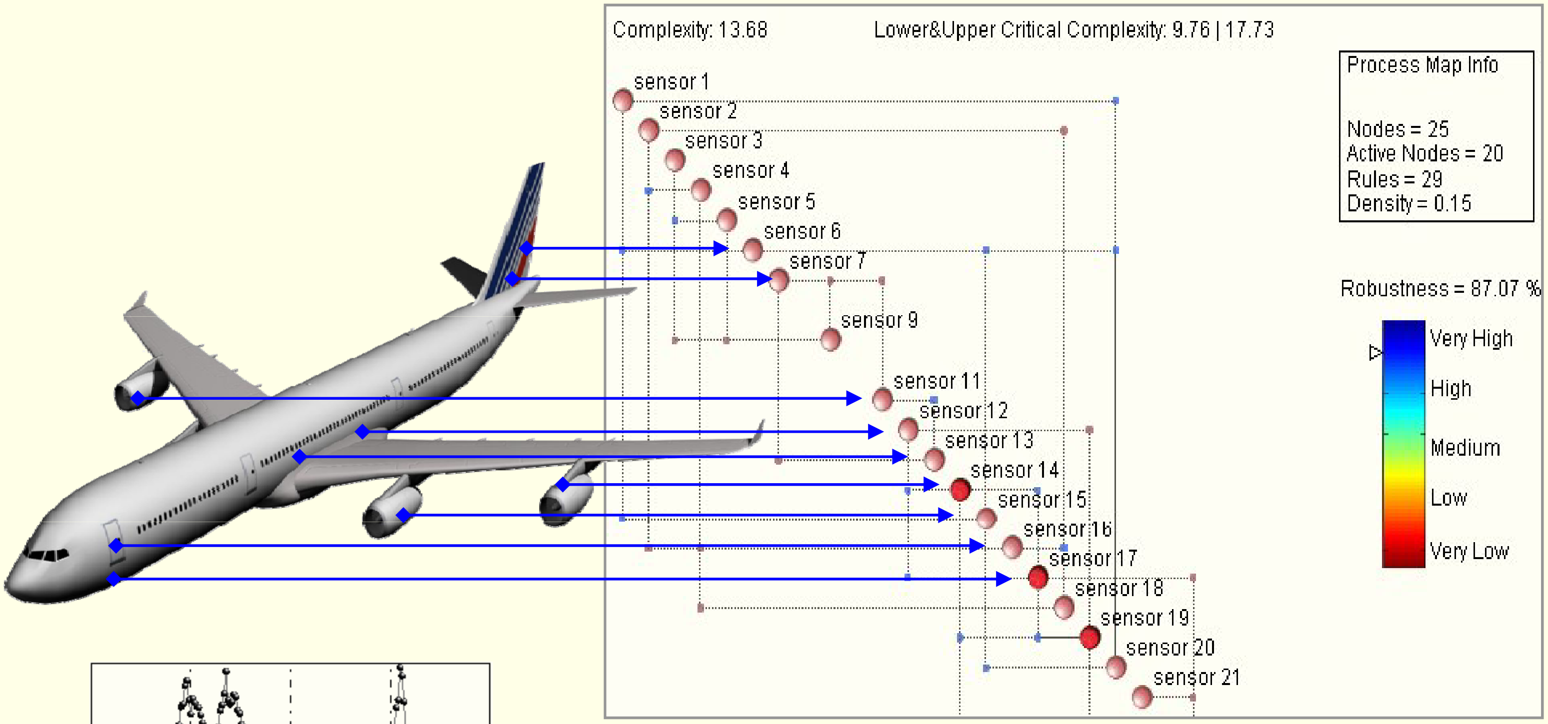
Power Turbine Monitoring

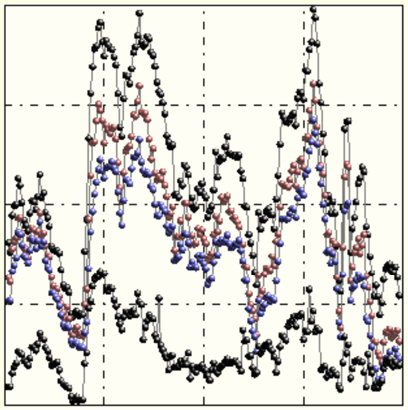


Air Traffic Monitoring



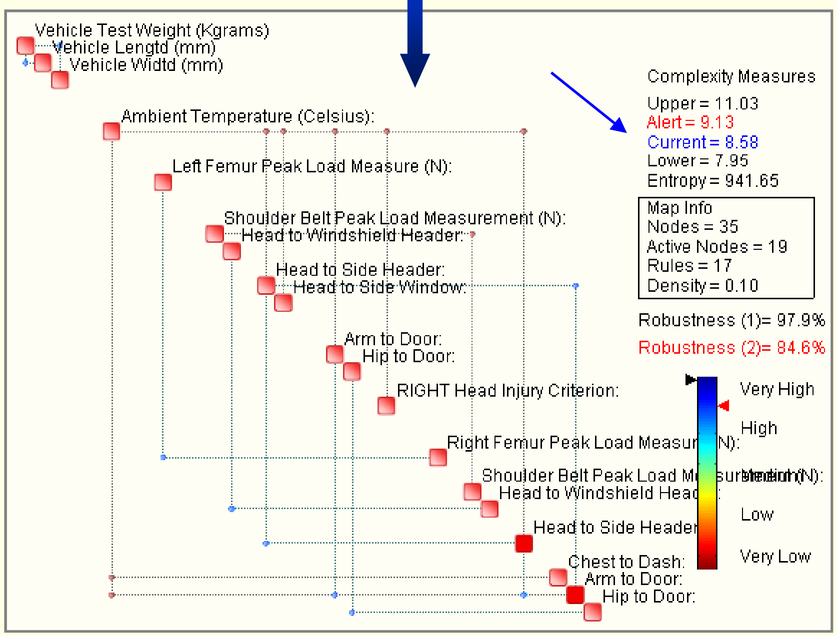
In-Flight Structural Health Monitoring



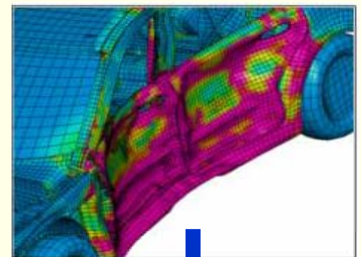


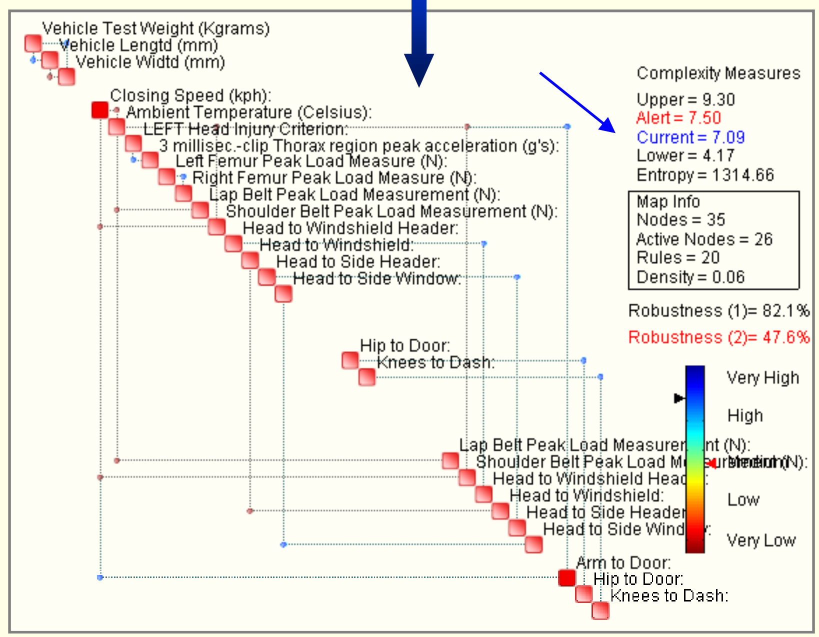
Measuring The Credibility of a Computer Model

Test



Simulation





How well does the numerical model emulate the real thing?

Model Credibility Index

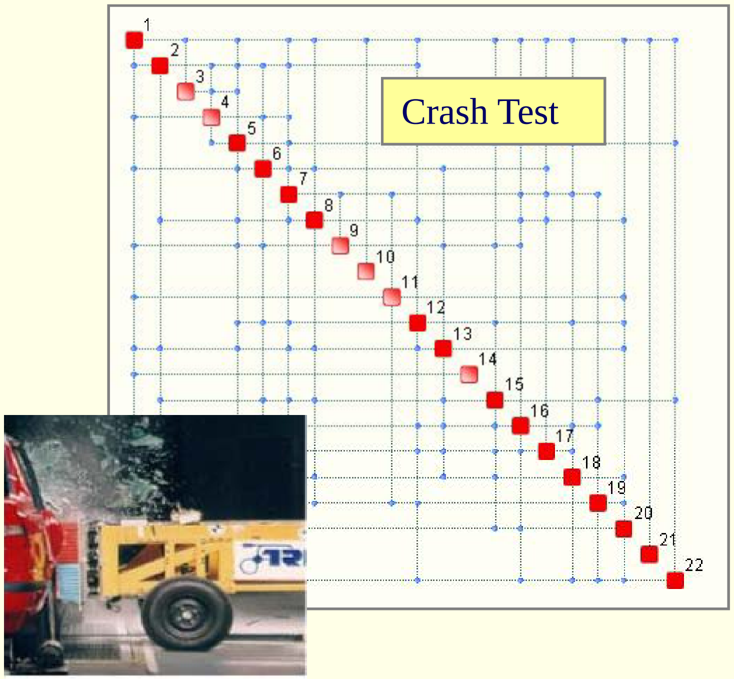
$$MCI_c = (C_{test} - C_{model}) / C_{test}$$

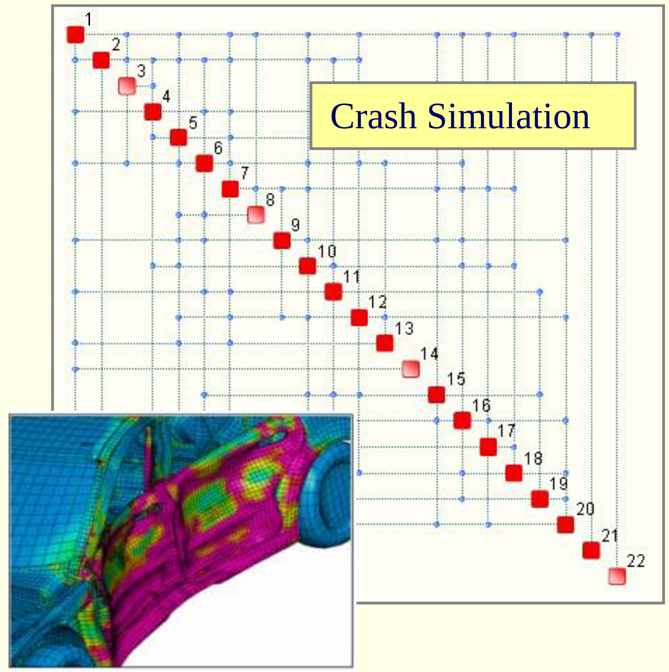
Weak Condition: $C_{test} = C_{model}$

- $C_{test} > C_{model}$ - Model (generally) misses physics
- $C_{test} < C_{model}$ - Model (generally) generates noise

Complexity measures the amount of structured information

Measuring Model Credibility – Process Map Topology

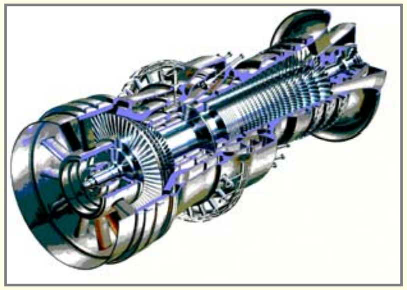




Strong Condition: **Map** $_{test}$ = **Map** $_{model}$

- **$MCI_t = (T_{test} - T_{model}) / T_{test}$**
- Based on this index, the credibility of this industrial crash model is 0.8

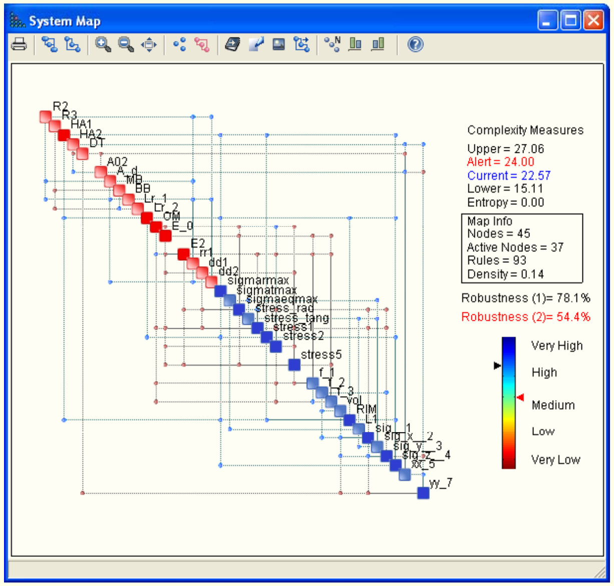
From Data to Knowledge



Model

Simulation

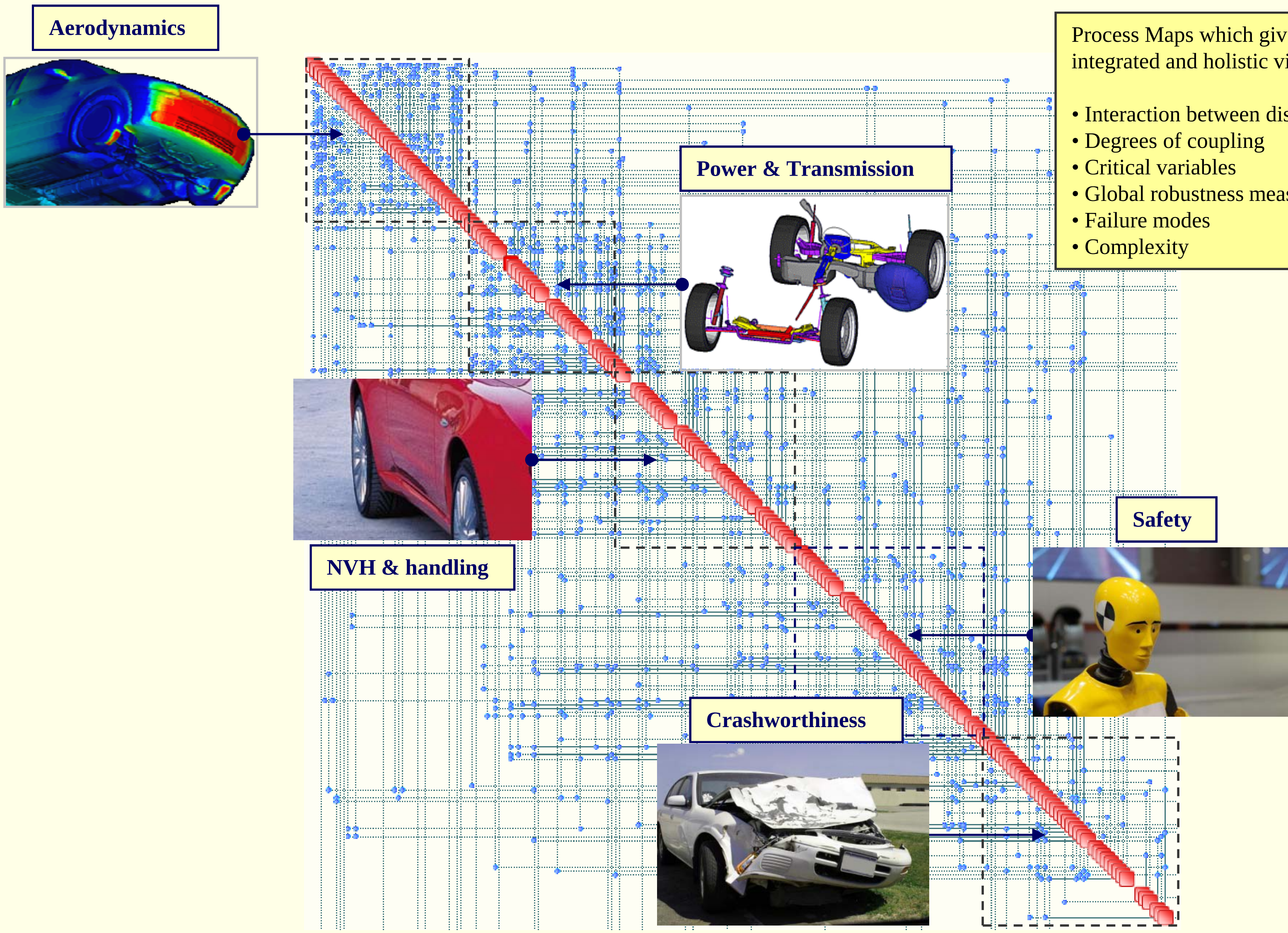
Data



Knowledge Map

A dynamic and inter-related set of rules constitutes a body of knowledge which can evolve in time as new data is gained. Such maps allow users to understand how sophisticated systems really work, how disciplines interact, which potential failue modes exist and provide measures of vulnerability (robustness).

Complexity-Based CAE – A Systems Approach



Process Maps which gives Users an integrated and holistic view of:

- Interaction between disciplines
- Degrees of coupling
- Critical variables
- Global robustness measures
- Failure modes
- Complexity

Is Optimality Convenient?

Engineering complex systems

The emergent properties of complex systems are far removed from the traditional preoccupation of engineers with design and purpose.

J. M. Ottino

Complex systems can be identified by what they do (display organization without a central organizing authority — emergence), and also by how they may or may not be analysed (as decomposing the system and analysing subparts do not necessarily give a clue as to the behaviour of the whole). Systems that fall within the scope of complex systems include metabolic pathways, ecosystems, the web, the US power grid and the propagation of HIV infections.

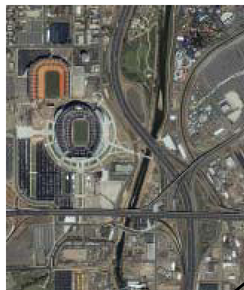
Complex systems have captured the attention of physicists, biologists, ecologists, economists and social scientists. Ideas about complex systems are making inroads in anthropology, political science and finance. Many examples of complex networks that have greatly impacted our lives — such as highways, electrification and the Internet — derive from engineering. But although engineers may have developed the components, they did not plan their connection.

The hallmarks of complex systems are adaptation, self-organization and emergence — no one designed the web or the metabolic processes within a cell. And this is where the conceptual conflict with engineering arises. Engineering is not about letting systems be. Engineering is about making things happen, about convergence, optimum design and consistency of operation. Engineering is about assembling pieces that work in specific ways — that is, designing complicated systems.

It should be stressed that complex is different from complicated. The most elaborate mechanical watches are appropriately called *très compliqué*, for example, the Star Caliber Patek Phillipe has 10^3 parts. The pieces in complicated systems can be well understood in isolation, and the whole can be reassembled from its parts. The components work in unison to accomplish a function. One key defect may bring the entire system to a halt; complicated systems do not adapt. Redundancy needs to be built in when system failure is not an option.

How can engineers, who have developed many of the most important complex systems, stay connected with their subsequent development? Complexity and engineering seem at odds — complex systems are about adaptation, whereas engineering is about purpose. However, it is robustness and failure where both camps merge.

Consider the recent debate of the balance between performance and risk. Many systems self-organize to operate in a state of optimum



More than the sum of its parts: complex systems, such as highways, are constantly evolving.

performance, in the face of effects that may potentially destroy it. However, the optimal state is a high-risk state — good returns at the price of possible ruin. Most engineers are risk adverse, and would prefer to eliminate the probability of catastrophic events. Recent work borrows concepts from economic theories (risk aversion, subjective benefit of outcomes) and argues that one can completely remove the likelihood of total ruin with minor loss of performance. This falls squarely in the realm of engineering, but the discussion has been driven by physics.

Engineers might also learn from social scientists. In social sciences, there is no such luxury as starting *de novo* — systems are already formed, one has to interpret and explain. Many engineering systems, such as the web or the US power grid, also fall into this category. How will they behave? How robust are they? How might they fail?

Although systems where self-organization has already happened present challenges, there are also opportunities in situations where self-organization can be part of the design. Could we intelligently guide systems that want to design themselves? Is it possible to actually design systems that design themselves in an intelligent manner? Self-organization and emergence have been part of materials science and engineering for quite some time, after all, lasers and superconductivity depend on collective phenomena. Emergent properties should strike a cord in materials processing, and also in the nanoworld. At larger scales, there is already work in directed self-assembly and complex dissipative systems, systems that organize when there is energy input. However, practical processing by self-assembly is still not a reality, and there is work here for engineers.

But the choice need not be just between designing everything at the outset and letting systems design themselves. Most design processes are far from linear, with multiple decision points and ideas 'evolving' before the final design 'emerges'. However, once finished the design itself does not adapt. Here, engineers are beginning to get insight from biology. In biological systems, the emergence of function — the ability of a system to perform a task — can be guided by its environment, without imposing a rigid blueprint. For example, just like the beaks of Darwin's finches, a finite-element analysis of a component shape such as an airfoil can evolve plastically through a continuum of possibilities under a set of constraints, so as to optimize the shape for a given function.

Engineers calculate, and calculation requires a theory, or at least an organized framework. Could there be laws governing complex systems? If by 'laws' one means something from which consequences can be derived — as in physics — then the answer may be no. But how about a notch below, such as discovering relationships with caveats, as in the ideal gas 'law', or uncovering power-law relationships? Then the answer is clearly yes.

Advances will require the right kinds of tools coupled with the right kind of intuition. However, the current engineering courses do not teach about self-organization, and few cover computer modelling experiments.

Despite significant recent advances in our understanding of complex systems, the field is still in flux, and there is still is a lack of consensus as to where the centre is — for some, it is exclusively cellular automata, for others it is networks. However, the landscape is bubbling with activity, and now is the time to get involved. Engineering should be at the centre of these developments, and contribute to the development of new theory and tools. ■

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FURTHER READING

Ball, P. *Critical Mass* (Heinemann, Portsmouth, 2004).
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performance, in the face of effects that may potentially destroy it. However, the optimal state is a high-risk state — good returns at the price of possible ruin. Most engineers are risk adverse, and would prefer to eliminate the

In highly turbulent environments, seeking optimality is unjustified. In fact, optimal designs are inherently fragile. Robust solutions should be sought instead. This can be accomplished not by maximising (arbitrary) objective functions but by accepting compromises in terms of performance and seeking simpler solutions to problems.

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Q&A Session

Using the Q&A tool, please submit any questions you may have for our panel.

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Thank you!

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