Developing Complex MIL/Aerospace SoS at Minimum Risk and Cost

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INTRODUCTION

THE AEROSPACE SYSTEM OF SYSTEMS DESIGN CHALLENGE

- Aerospace systems are complex SoS that have to be designed to cope with rapidly changing architectures and challenges.
- Their main technological advancements today are driven by the progress in readily available electronics and the ability to develop disruptive systems rapidly at minimum time, cost, weight, power consumption and maximum security (before competitor).
- There are no engineers who will understand the complex interactions of such SoS without an executable model. The development can therefore only be carried out with mathematical models at mission level. The elements of models have to be physical laws or other validated facts.

The challenge is to develop methods and software for design/development that minimize the risk of development of these highly complex SoS

What are complex aerospace SoS?

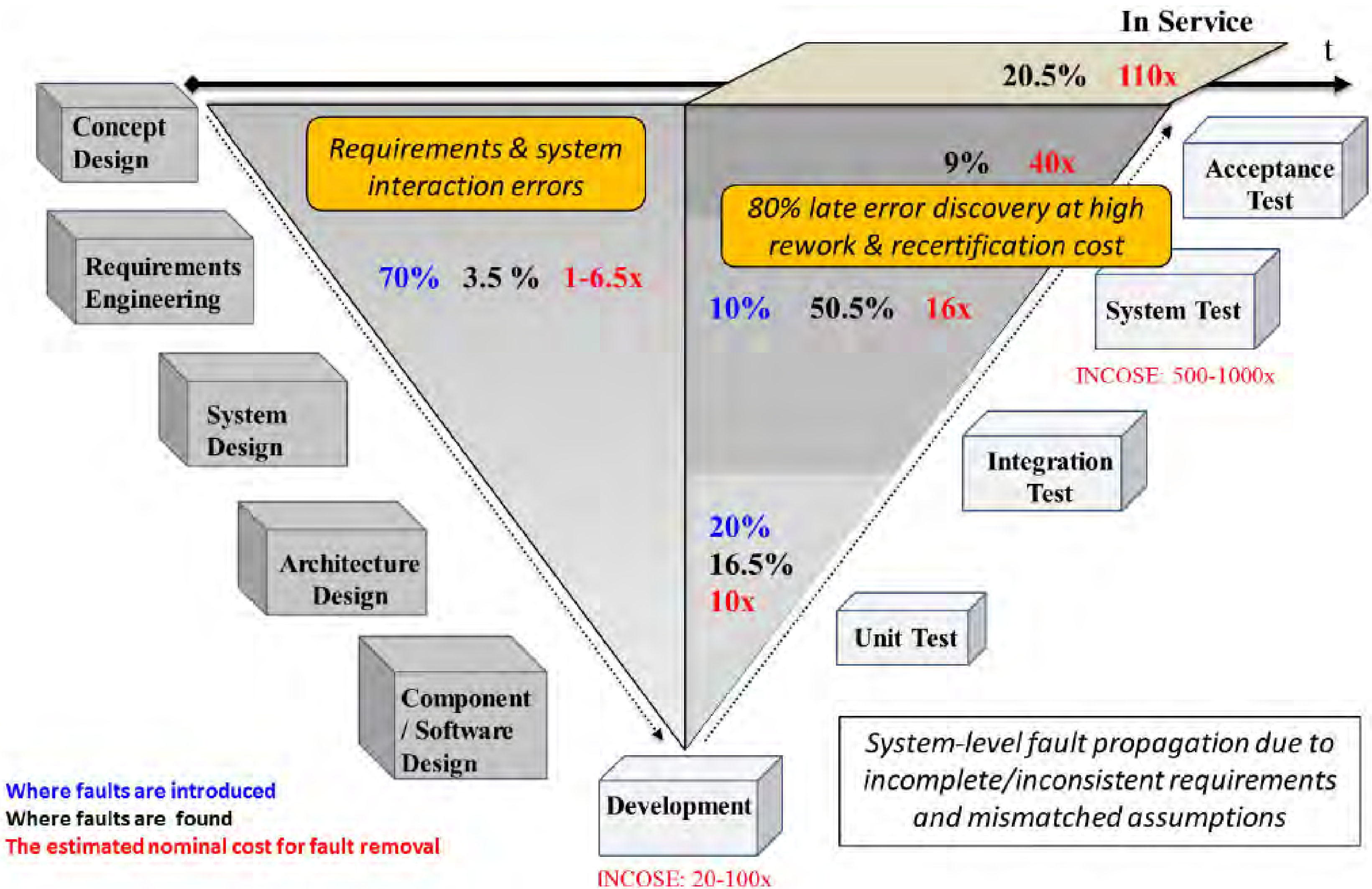
All aerospace vehicles are multi-disciplinary, dynamically coupled systems of systems (SoS), with dynamical interactions of,

- Vehicle
- Pilot (and/or Robotic system)
- Environment
- Propulsion system
- Avionics system
- Networked digital electronics
- Payload
- Coupled autonomous vehicles



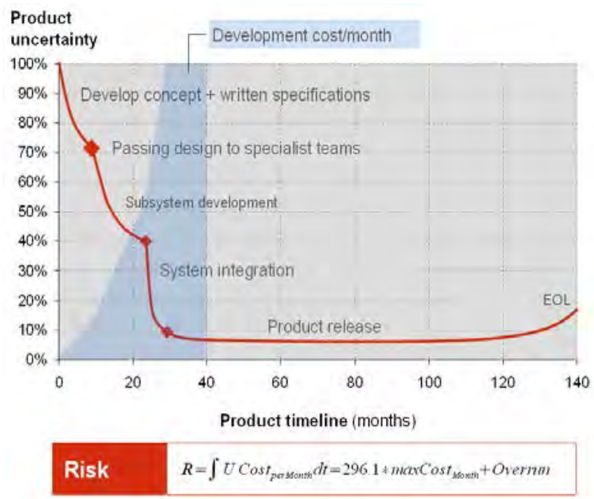


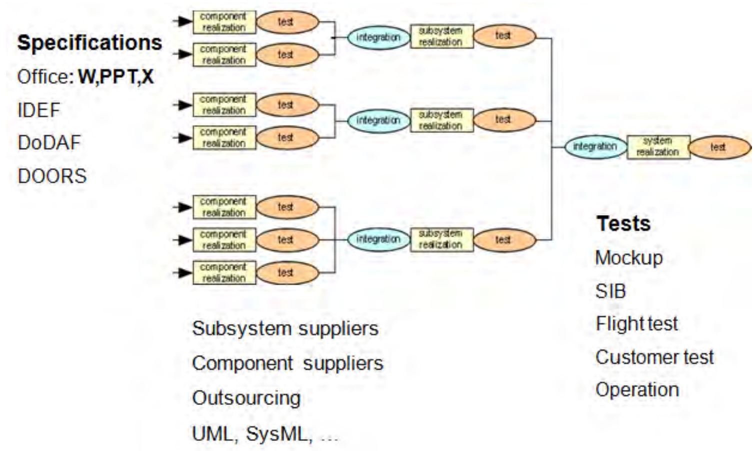

Results of current industry design methods



Aerospace made fantastic progress, but recently runs into cost and time overruns of >$100B/year

Risk of Classical Design Flow





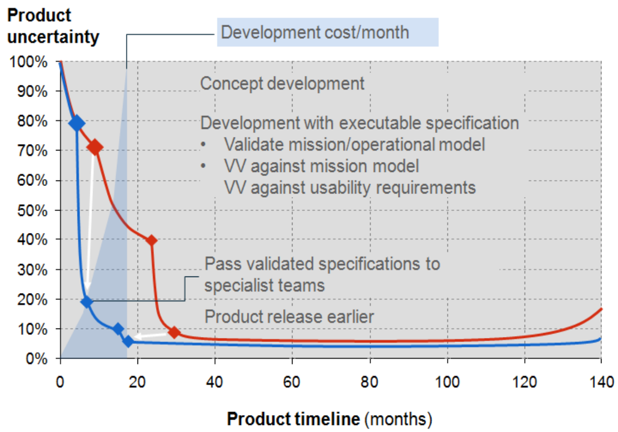
→ Classical Design Flow maximizes risk

→ Cannot optimize for top level requirements

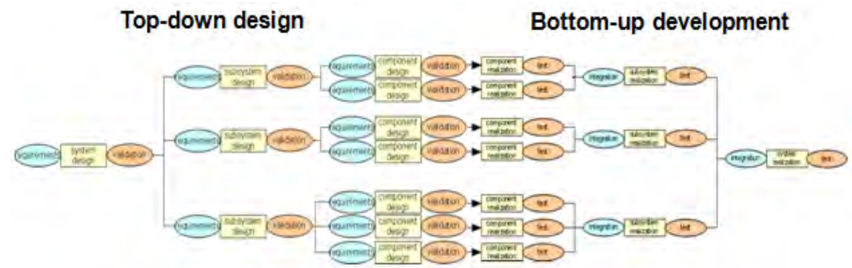
→ Has lead to development time and cost overruns, project cancellations, and thousands of dead pilots in WW I

→ Is unsuitable to develop disruptive technologies

Mission Level MIL/Aerospace design flow



Risk $R_{MLD} = \int U\ Cost_{perMonth}dt = 61.0 \square max\ Cost_{Month}$



Develop executable specification

- Architecture: resources, protocols
- Function
- Mission
- Usability

Optimize Architecture

Automate specification validation over range of uncertainties, requirements, environment

Validate implementation against executable specification

Update specification with implementation compromizes

Performe coverage analysis during flight tests

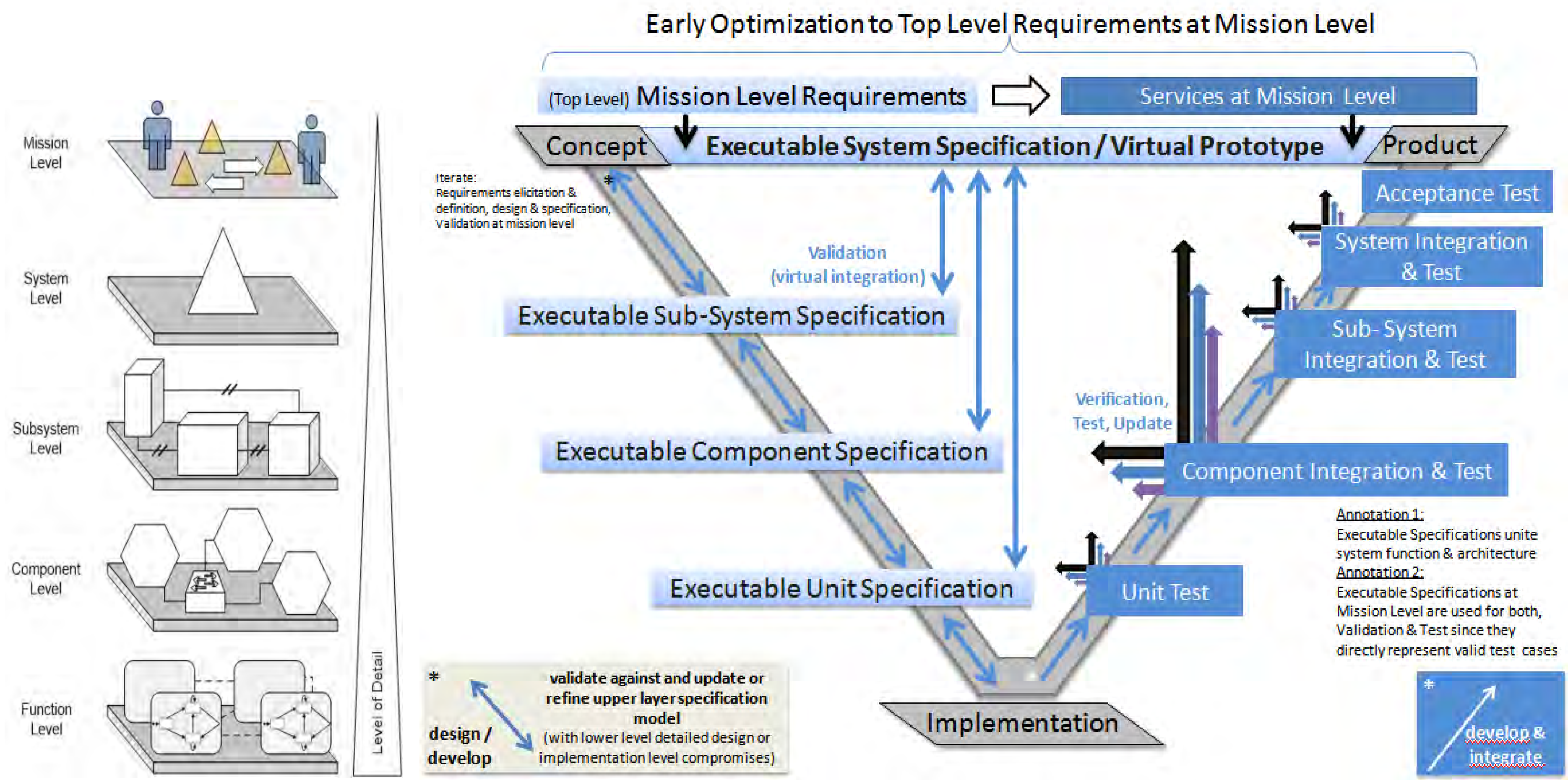
Use ES/Virtual prototype for training

Use validated ES for development of next A/C

- MR-MBSE design integrates top-down design with bottom-up development
- DoD requires that developed executable specifications are updated and validated during all phases of development, including concept development, technology development, subsystem development, integration, test, training and life cycle management
- Both Boeing and Airbus use this approach

MINIMUM RISK DESIGN

DEVELOPMENT PROCESS



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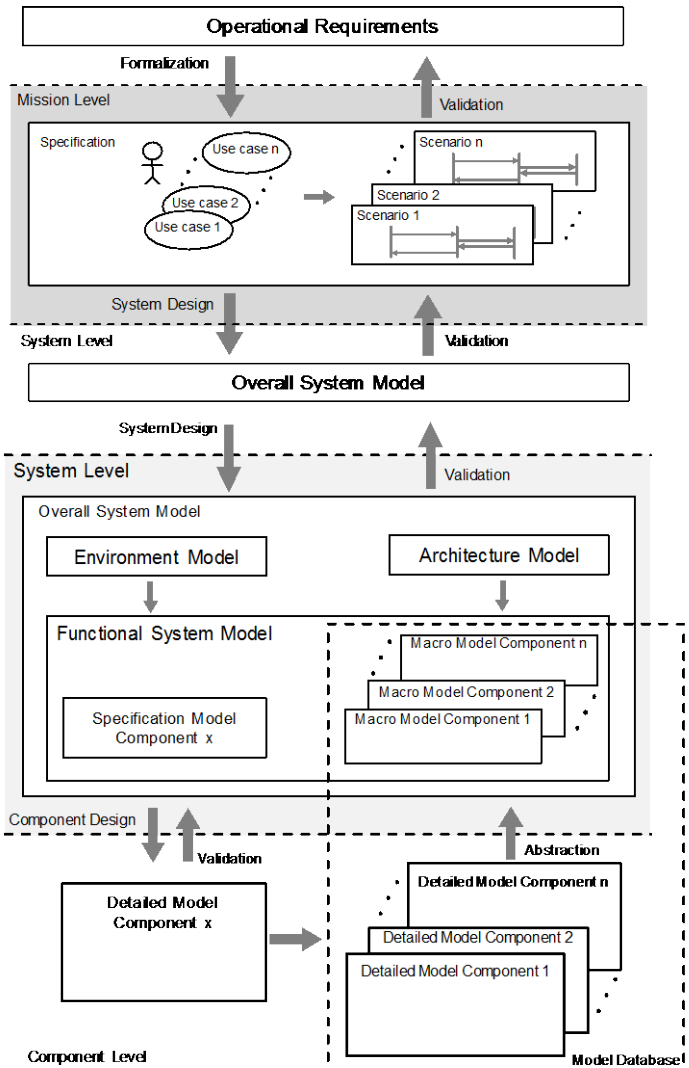
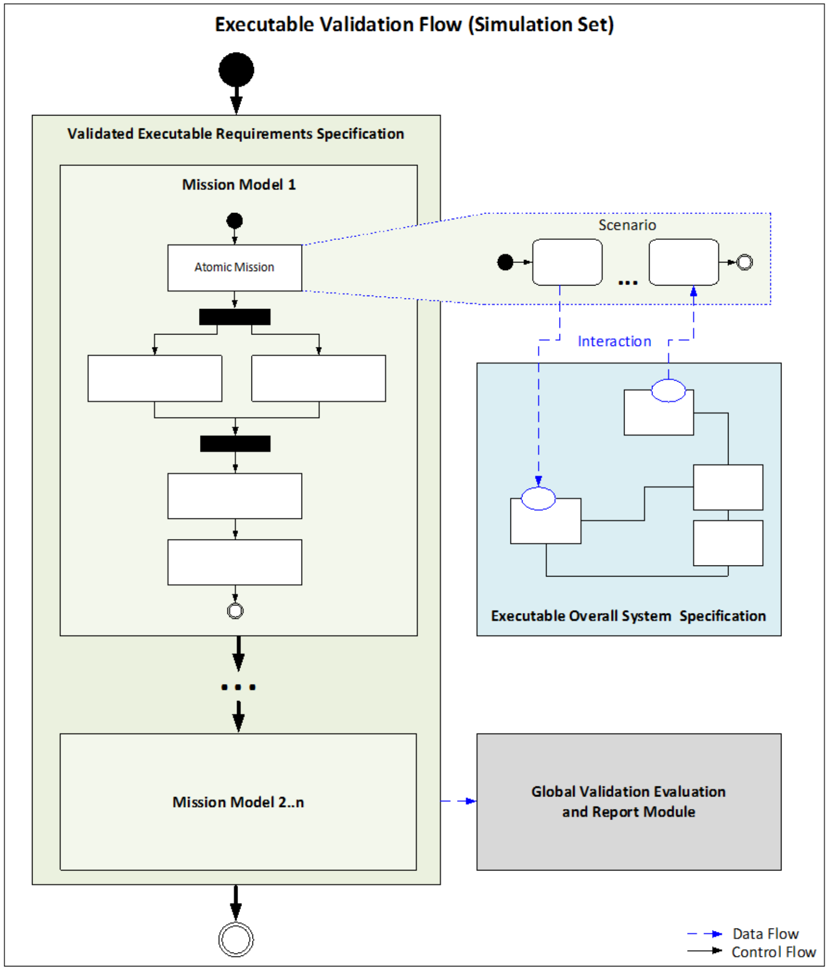
MISSION LEVEL DESIGN WORKFLOW

FROM REQUIREMENTS TO EXECUTABLE SPECIFICATION





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GENERAL FEATURES

Provide Graphical / Block-oriented Modeling Capabilities
- modular modeling approach with hierarchical diagrams
- statechart or flowchart design capabilities
- plug-&-play design capabilities

Modeling of System Environment
- multi-domain system context
- behavior & architecture models

Modeling of Function / Behavior
- logical functions / processes

Modeling of System Architecture
- hardware (e.g. electronic control units)
- resources (e.g. memory, power)
- interfaces and data transmission channels (including network, middleware / protocols)
- operating systems

Modeling of Missions and Services
- driver and evaluation model development
- formalized mission model development components
- formalized use case / misuse case and scenario model development components

Modeling of Executable Workflows and Simulation Sets
- for modeling of design flow, validation flow and optimization flow
- provide formalized components & interfaces

Support Multiple Simulation Domains
- timed (e.g. discrete event)
- untimed (e.g. synchronous data flow)

Minimum Risk Model-based Systems Engineering Design and Validation Environment

Support Distributed Simulation / Monte-Carlo Simulation (MCS)
- distribute simulations to different platforms
- MCS to perform range of simulations and for extended analysis of "what if" scenarios

Visualization and Animation
- for virtual prototype development
- to control / operate simulations
- to evaluate simulation results
- to develop custom HMIs / GUIs

Coupling to External Tools (task-specific)
- provide API
- support standardized file formal (e.g. XML)

Support Distributed Teamwork
- configuration / version management

Data / Parameter Model Editor
- create and organize data models
- support ordinal, elementary and composite data types
- create, typecast and organize parameters

Documentation Generation
- generation of model documentation
- to document / trace requirements
- to aid distributed teamwork
- generate validation reports

Link to External Devices
- for virtual prototypes
- for hardware-in-the-loop testing

Fully supported by MLDesigner
Extension feature (to be provided)

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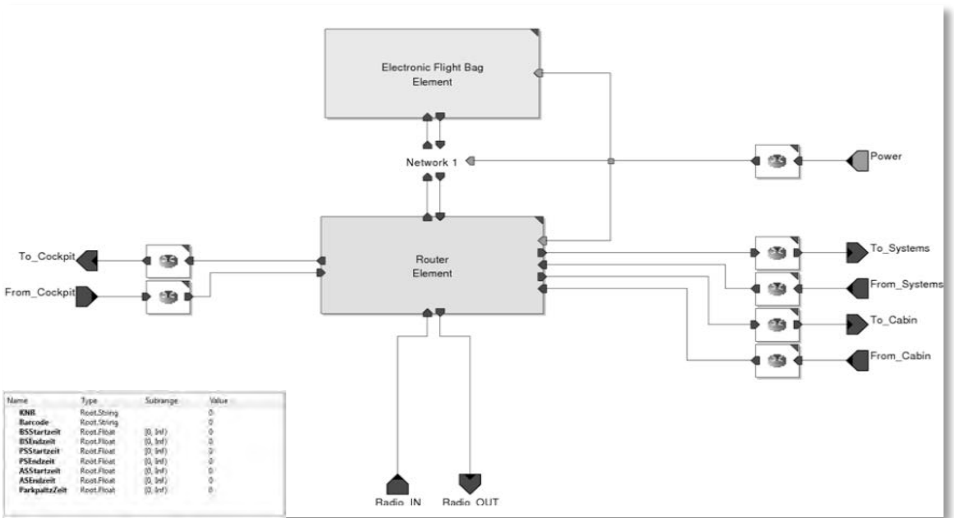
EXECUTABLE SPECIFICATION



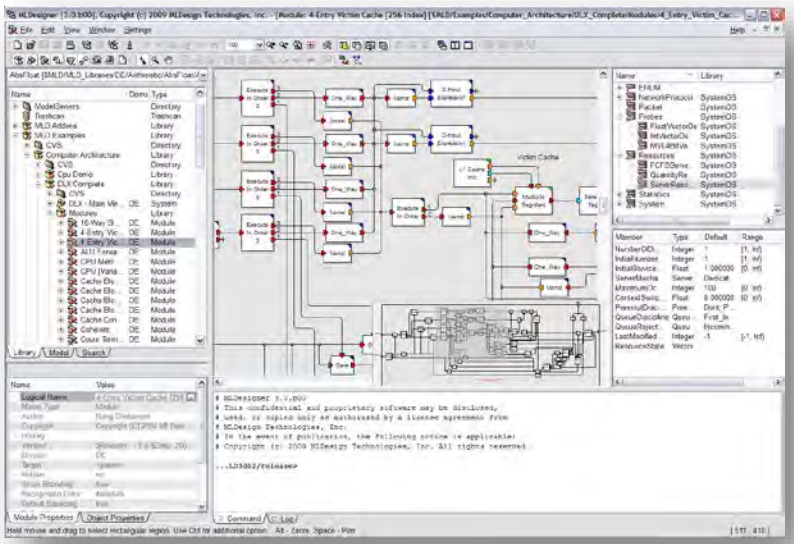
KEY CHARACTERISTICS

- Modeling & simulation of complex systems, systems of systems and processes at mission level (use-case and test-case driven)
- Free modeling of data & data transport systems for any purpose
- Arbitrary level of abstraction (top-down, middle-out)
- User defined extensions with means of C/C++ or any other programming language w/ C++ bindings
- Interfacing for x-in-the-loop approaches
- Interfacing to arbitrary tools via extensions (e.g.: database systems, reporting engines)
- Lightweight XML model storage e.g. for version control systems, configuration management and linking with requirement management tools

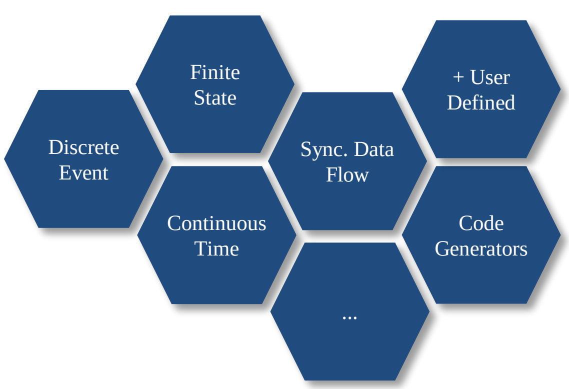
BUSINESS BENEFITS OF MLDESIGNER

- Analyze dependencies in complex system designs
- Visualize and study complex sys.-behaviour
- Test subsystem integration during concurrent development phases (Middle-out)
- Detect, disclose and track inaccurate/faulty system requirements to its origins

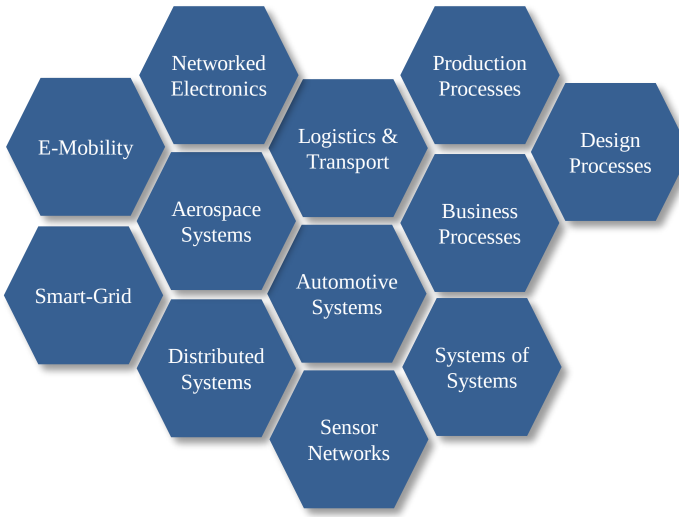
MLDesigner



MODELS OF COMPUTATIONS



FIELDS OF APPLICATIONS



GENERAL BENEFITS OF MLDESIGNER

- *Reduction of project/product risk & costs by using* ***virtual prototypes***
- *Early* ***optimization*** *of system design*
- *Early validation of* ***functional*** *requirements*
- *Evaluation of* ***non-functional*** *requirements*
- *Prototyping of* ***HID*** *(human interface device) for early* ***user-acceptance tests***
- *System models & results of analyses may be used in* ***product certification process***

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MRD 1: B777 development → MR-MBSE of networked systems

The design of the B777 included >200 ECUs that communicated over shared bus systems to save weight. To reduce the high risk of such a development Boeing introduced MR-MBSE of networked avionics systems.

- Performance level executable specifications + simulation with BONeS permitted
  - aircraft level analysis/validation of avionics/cabin systems
  - reliability analysis during concept development
- The B777 avionics development time was reduced 2x + achieved the highest availability of any aircraft

MRD 2: A380 ➔ Aircraft level specification validation of AFDX

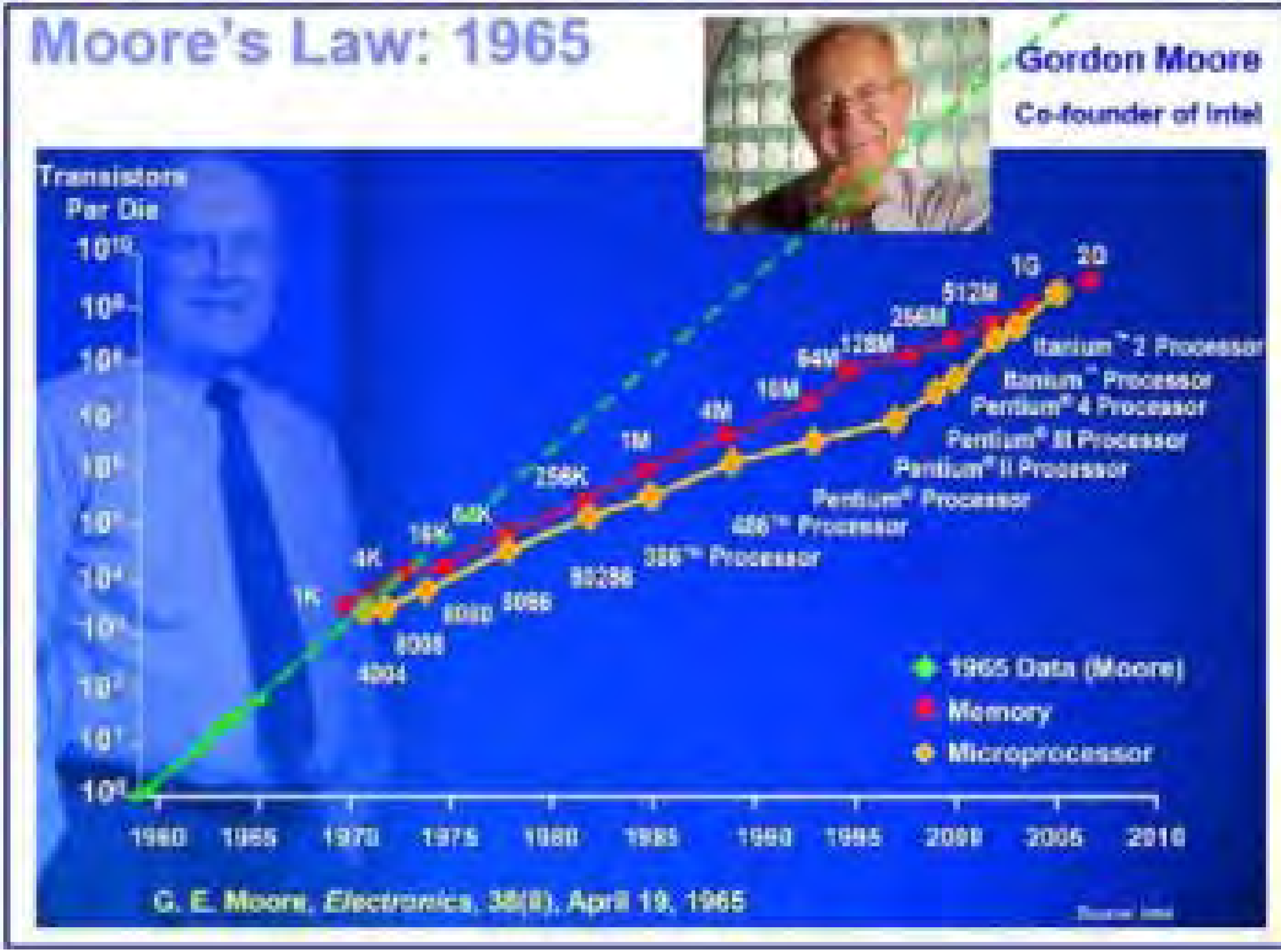
Development of a performance and architectural modeling and verification environment for A3XX AFDX based cabin systems

- The network models are used to make design performance trade-offs and architectural evaluations
- Traffic models used here are derived from trace data for the previous Arinc 629 based onboard network systems
- These models are used as a verification and configuration environment for the A3XX Network system
- Statistics collected include frame end-to-end latencies, switch latencies, switch memory requirements, switch throughputs, and switch queue statistics
- **Resulted in standards: ARINC 653, ARINC664P7**

Contract from Jean Paul Moreaux inventor of AFDX), Airbus and Honeywell

MRD-3: Intel Architectural Optimization

TRAINING IN MR-MBSE in 1995 resulted in MOOR'S LAW GOING UP IN 1996

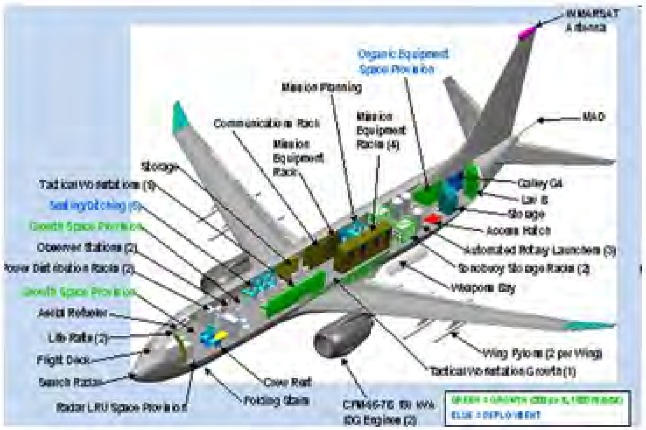


MRD 3: NavAir P-8A Multi Mission Maritime Aircraft

Providing modeling, simulation, and analysis technical support for B737 based P-8A Multi Mission Maritime Aircraft (MMMA) Program

After model based design approach by BAH with Extend failed, 2005 MLD was called in to provide modeling support and tool

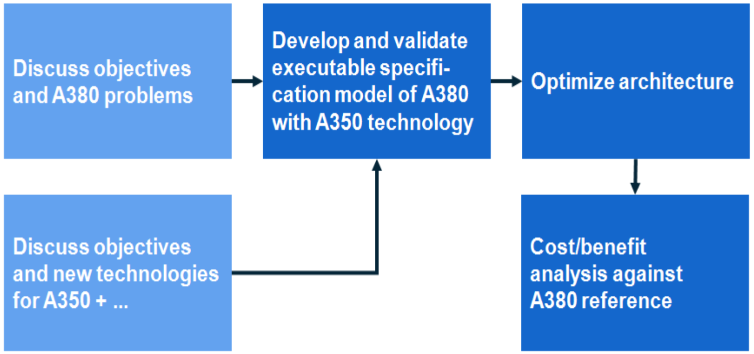
- Developed first executable specification of architecture, process and mission
- Formal executable specifications at aircraft level were introduced
- Model based architectural trade-off at mission/operational level
- Automatically generated html-files of models are integrated in LCM (Life Cycle Management System) and viewable in Browser over Intranet

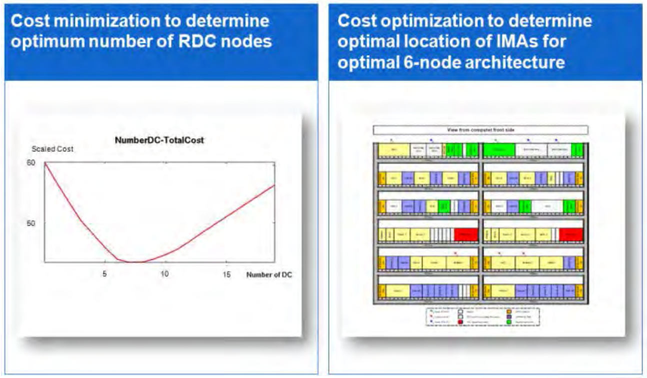


Result/Impact

Coverage analysis during flight test with MLDesgner based virtual prototype. Aircraft went into service in time without cost overruns. Life cycle management is carried out with virtual prototype. All first 100 missions were carried out faster or exactly as computed. NavAir gave Boing followon contract to integrate sensors of 2 other aircraft in P-8, in order to be able to terminate the other aircraft.

MRD 4: Aircraft level optimization of avionics architecture





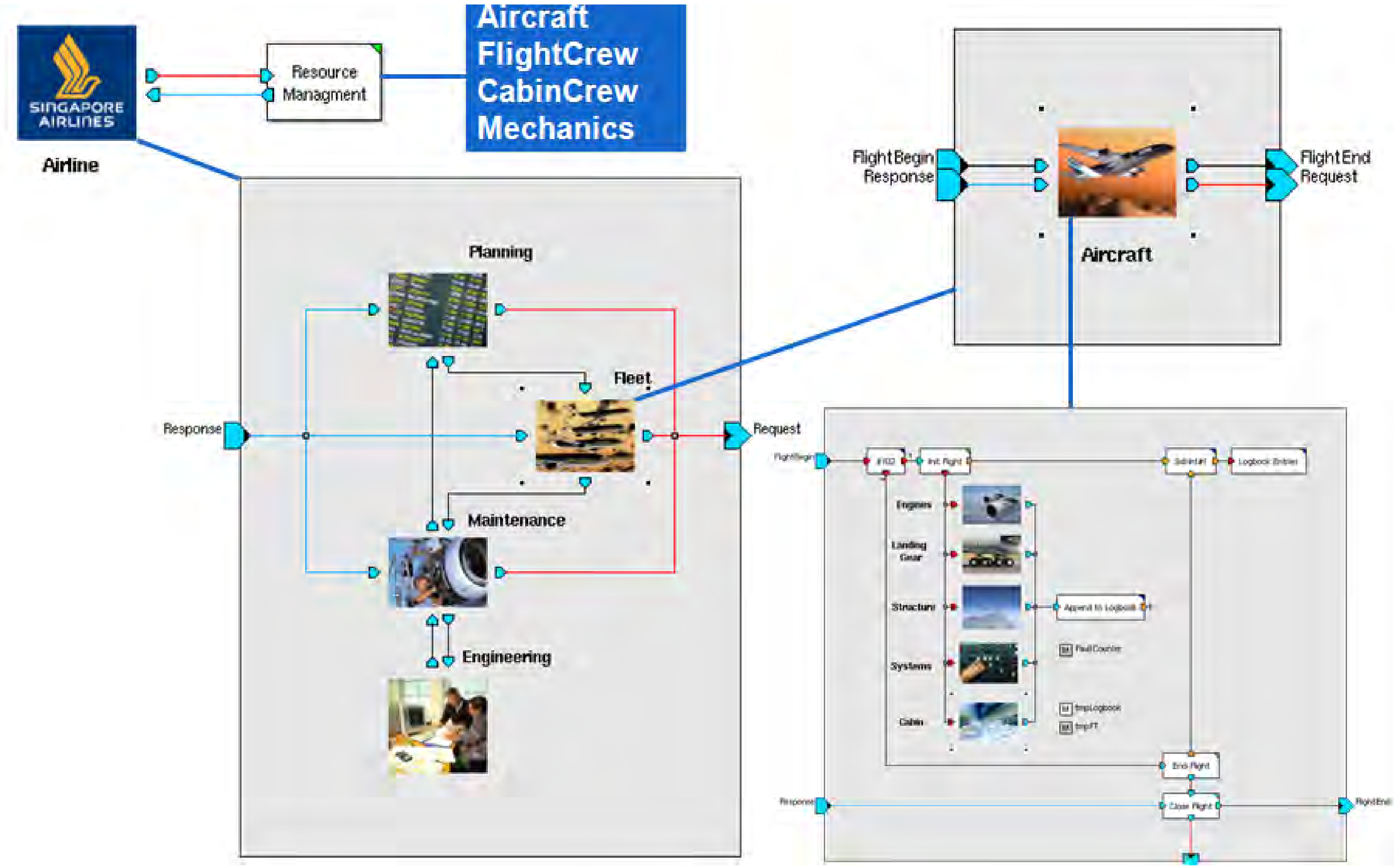
Performance item	Reference system	Optimized system
Cost of architecture [%]	100	28
Reduction of cables [%]		68
Weight of architecture [kg]	280.06	201.00
Weight of cables [kg]	108.21	29.15
Length of cables [feet]	1,531.46	453.84
MTBF [h]	55,632.88	57534.15
MTTR [h]	31.63	29.89
MTBUR [h]	49,164.46	50,874.30
Availability	0,99	0,999999999999999

-$1.77M/a/c

Further optimization w/new Airbus technology resulted in a switched architecture a/c design with x200 weight reduction of cables and >15% fuel saving + Airbus patents

MRD 5: Optimize Aircraft Architecture/Maintenance/Operation for Transport Availability

Model aircraft down to LRU level, airline operation, and maintenance, including logistics



Optimization of A320 introduction at AA achieved 99.9% availability of first 25 of 260 aircraft.

REFERENCE CUSTOMERS

SOME USERS OF MLDESIGNER

ORDERMAN
MOTOROLA
üstra
BOSCH
BOEING
Honeywell
SIEMENS
VDO
AIRBUS
Rockwell Collins
GM
ERICSSON
intel
PHILIPS
TOLL COLLECT
American Airlines
SAIC
LOCKHEED MARTIN
DLR
infineon
philotech
FHE FACHHOCHSCHULE ERFURT UNIVERSITY OF APPLIED SCIENCES
TECHNISCHE UNIVERSITÄT ILMENAU
HAW HAMBURG

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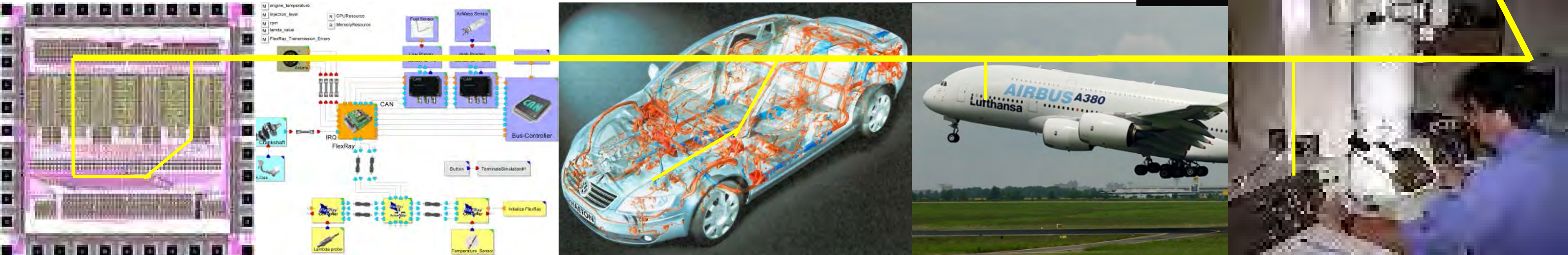
MR-MBSE technology has been applied to design/analysis of:

- Networked systems
  - On Chip, Avionics, Aircraft, RPV, AUV, Satellites, Cars, Comm., Networked Computers
  - Complex software systems
  - Reconfigurable embedded systems, Software radios, …
  - Multi-core architectures
  - Reconfigurable FPGAs

- Analysis, design and optimization of processes
  - Product design, development and quality processes
  - Logistics and SMC processes
  - Production processes
  - Organizational processes

TETRA, GSM, GPRS, EDGE, UMTS, AFDX, USB, LIN, FlexRay, TTNT, QNT, 802.11_{a-n}, 15, 16, SatCom



Summary

- It was shown that dynamically couples SoS of highest complexity and highest safety and security requirements can be developed without cost and time overruns using MR-MBSE technology
- For the example of aircraft development it was shown that this was only made possible by constant advancement in modeling, simulation and computer technology and close cooperation with domain experts
- It required
  - A small dedicated modeling and simulation team in the design office lead by an highly experienced engineer (Example: associated fellow)
  - A requirement of the executable specification/ virtual prototype to be a paid for deliverable (in MIL projects to customer)
  - A requirement that all integrations are first validated within the virtual prototype
  - All developers to have access to this virtual prototype, in order to be able to test disruptive new ideas for their impact on the system as used by the final customer/at mission level during design on the left hand side of the development **V**
- And permitted
  - Direct optimization for top level requirements at aircraft and service/mission level

More Details

Progress in MR-MBSE: 1980s

Challenge

- Multi-disciplinary Aero-servo-elasticity problem in a/c & s/c
- ACOSS (LM/SAIC-SCT)
- F-16CD (AFWAL/LM), AMRAAM (EGLIN), Minuteman,…
- F-16Delta: Intergrated Flight-Propulsion control
- RADC Req. for Networked MIL/Aerospace electronics with dynamic architectures

Solution

- SAIC developes unified language/tool CtrlC/ ModelC ➔Matlab/Simulink
- SAIC: Frequency dependent weighting in optimal control
- SAIC: Validated executable specifications (VES)
- SAIC: VES of integrated FCS passed to subsystem developers -> F-22
- Cadence: BONeS

Progress in MR-MBSE: 1990s

Challenge

- B777, A380
- RASSP (Tri-Service)
- Arch. opt. of Intel chips
- Iridium, Globalstar, Teledesic, EOS, …
- EOL BONeS
- MLD

Solution

- VES of networked electronics with BONeS
- LM-ATL/Cadence: Unified methodology: Spec. with SPW/BONeS ➔ 4x in 5Y

  Cannot solve DoD req for IoMT
- VES with BONeS (1995…)
- VES with BONeS/SatLab
- R/D for replacement >$1B , … did not work
- Cyberphysical sim MLDesigner

Progress in MR-MBSE 2000s

Challenge

- Aerospace Corp.
- TTNT (IoMT)
- P-8, Tanker a/c
- Intel Comm chips
- Airbus

Solution

- BONeS ➔ MLDesigner
- Rockwell Collins: OPNET ➔ MLDesigner
- VES from concept development to LCM with MLDesigner
- VES for UMTS/GSM chip w/MLDesigner reduced iterations from 4x to <=1 (dev time 9 month)
- A/C level and service level architecture optimization

MLDesigner Software System

Common MLDesigner GUI, Block Diagram Editor
Kernel, Simulation Control
XML Model Description, CVS

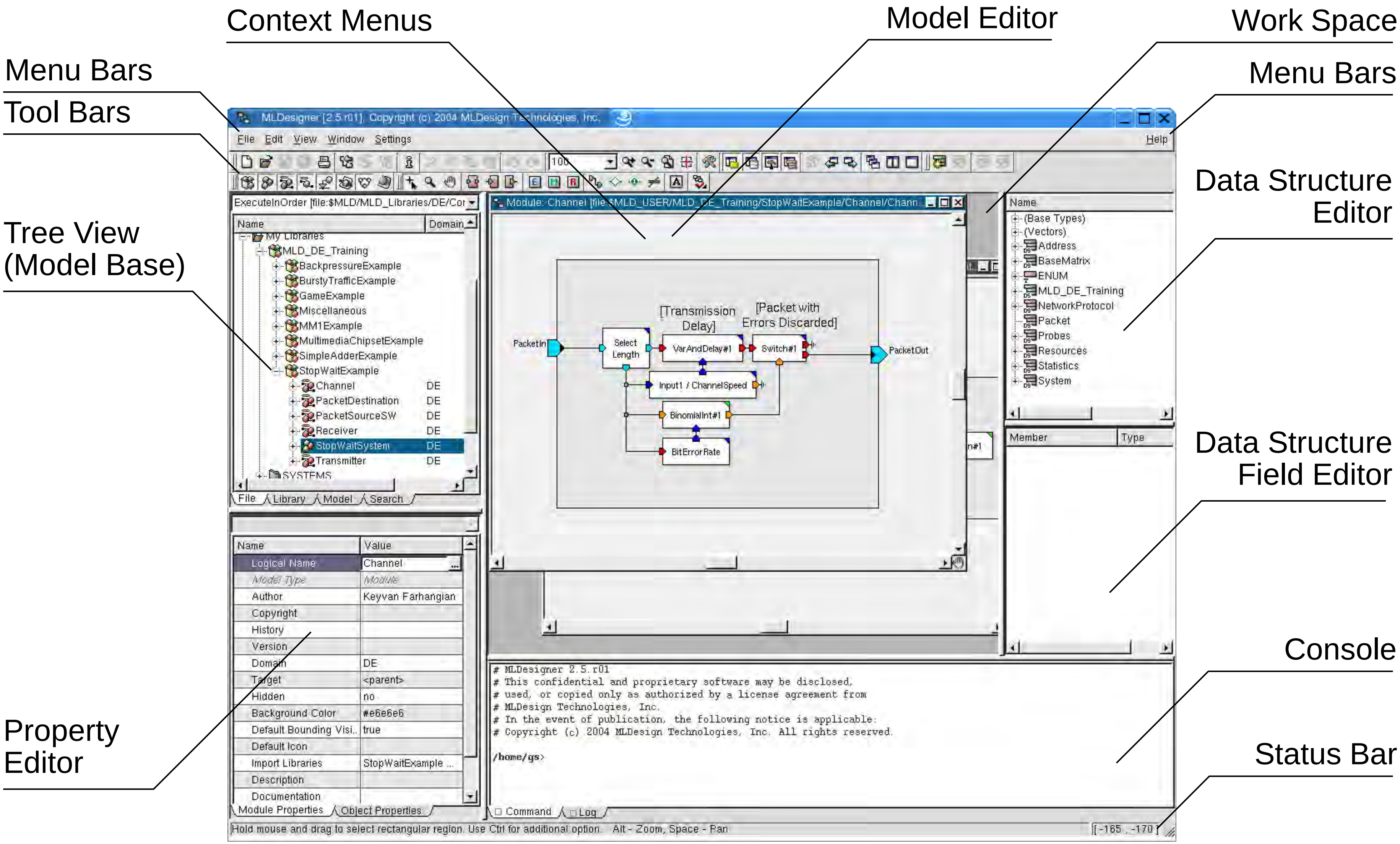
Design Domains
Discrete Event
FSM/StateChart
Static Data Flow
Dynamic Data Flow
Analog
NS2
Simulation Set
New ...

Libraries
Base Library
Add-on Libraries
802.11
Network Lib
Bus Systems
...
User Libraries

Interfaces
MATLAB
SatLab
Mathematica
Octave
GSB
Other Sim Tools
Other Applications
Hardware
OpenGL
Tcl/Tk
Altia

Conversion
BONeS => MLD
COSSAP => MLD
Ptolemy => MLD

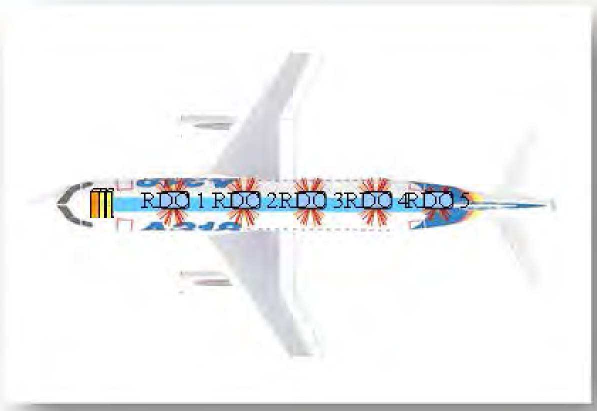
MLDesigner Software System



Avionics Network Architecture Optimization: The Goal

Traditional Avionics Network Layout

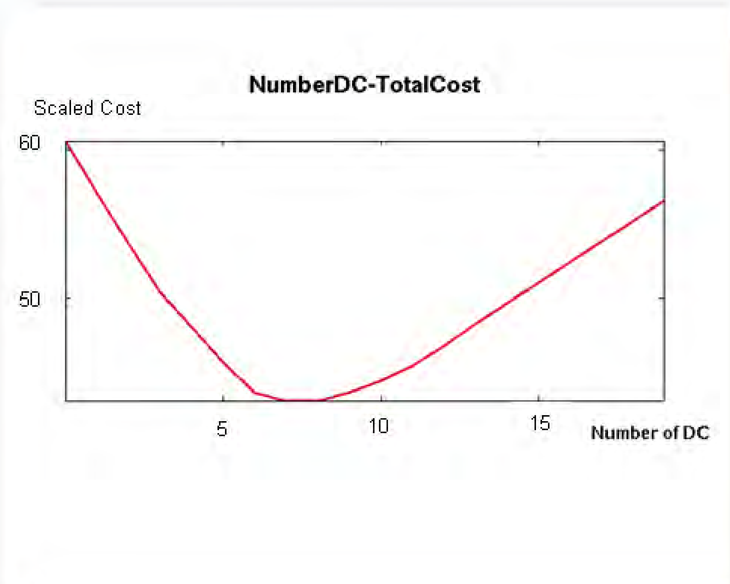
New Technology allows distributed Network layout



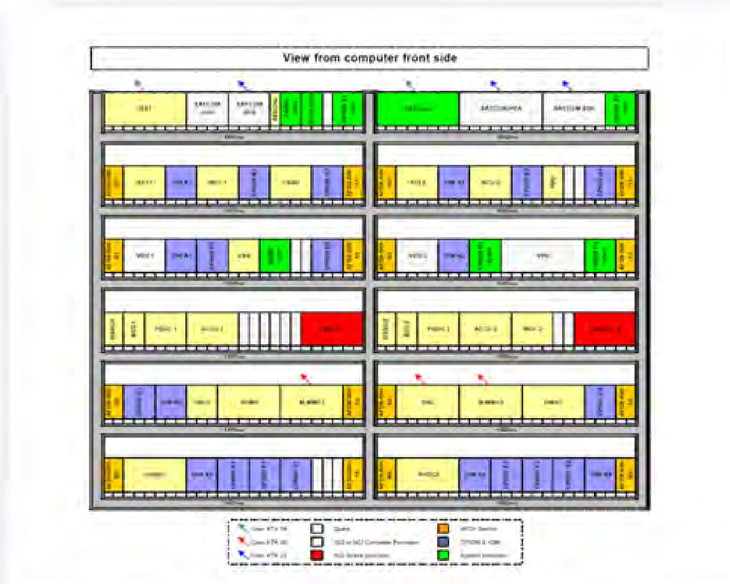
What is the minimum cost architecture that meets all requirements?

Avionics Network Architecture Optimization

Cost optimization to determine optimum number of nodes



Cost optimization to determine optimal location of IMAs for optimal 6-node architecture



Automated avionics network architecture optimization

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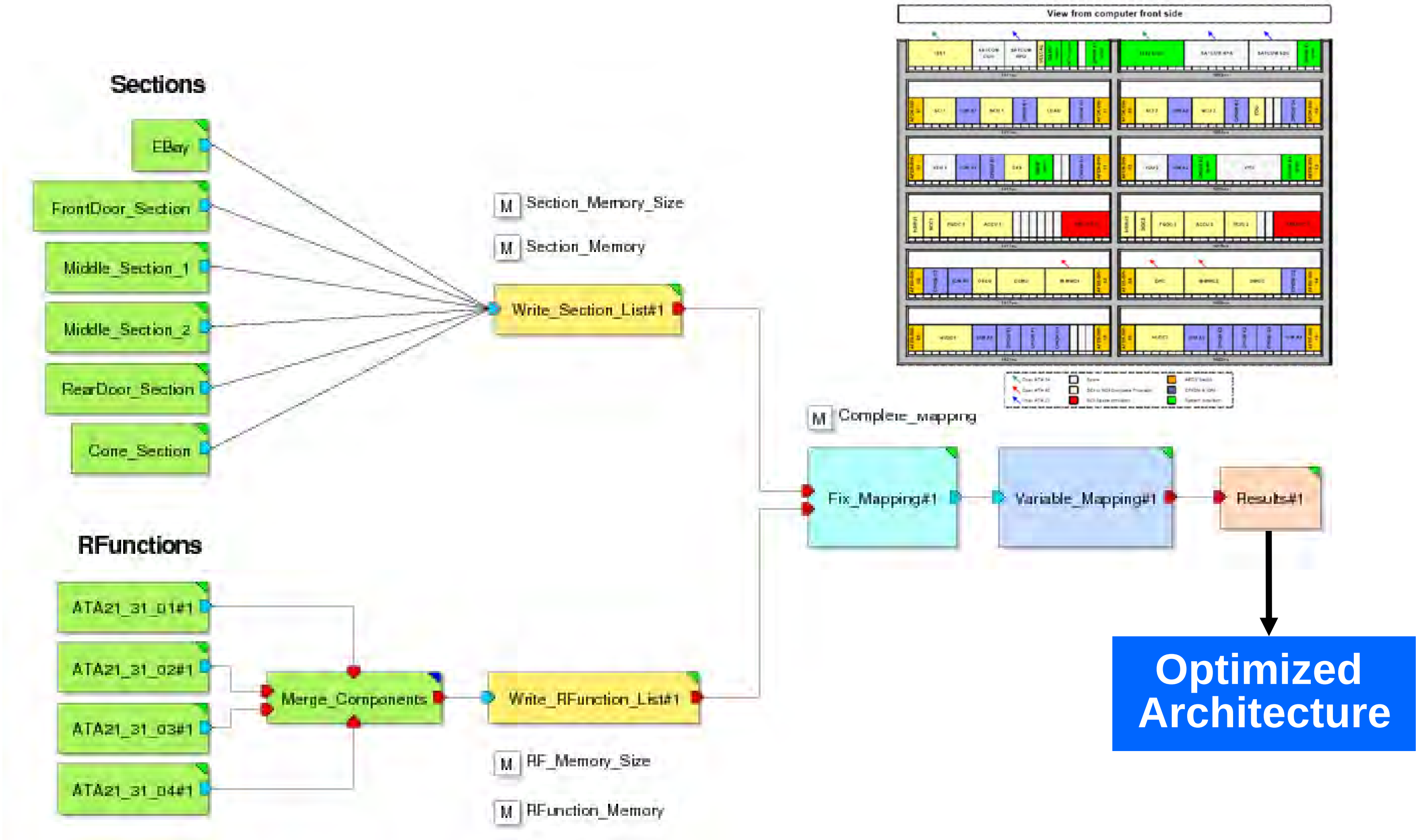
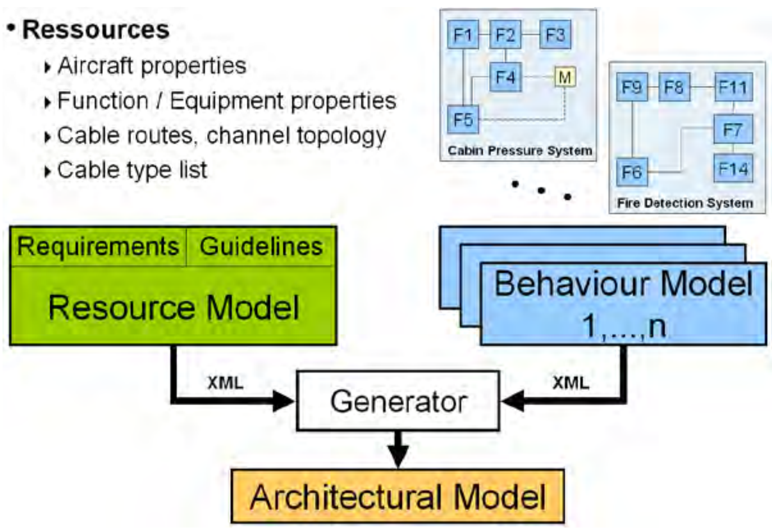
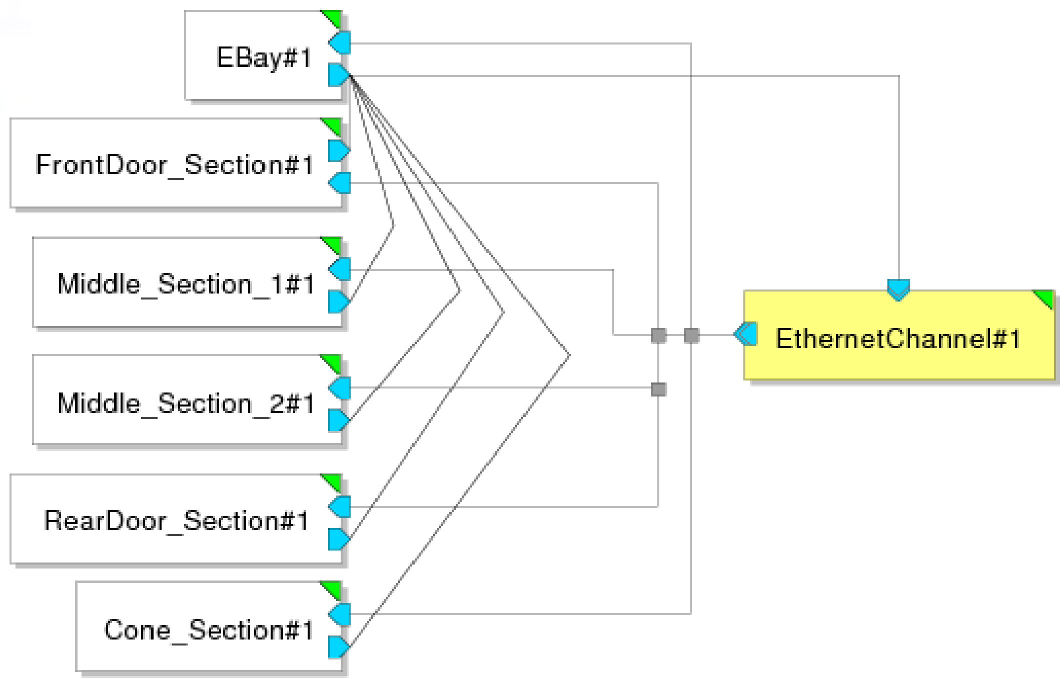


Automatic generated model of avionics network architecture + function

Mapping function into architecture





Analysis of executable specification of optimized architecture of environmental system

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Availability	0,99	0,999999999999999

An optimized configuration will result in significant improvements in cost, weight, development time and risk level

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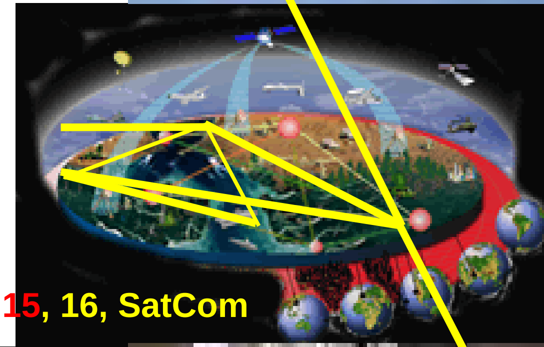

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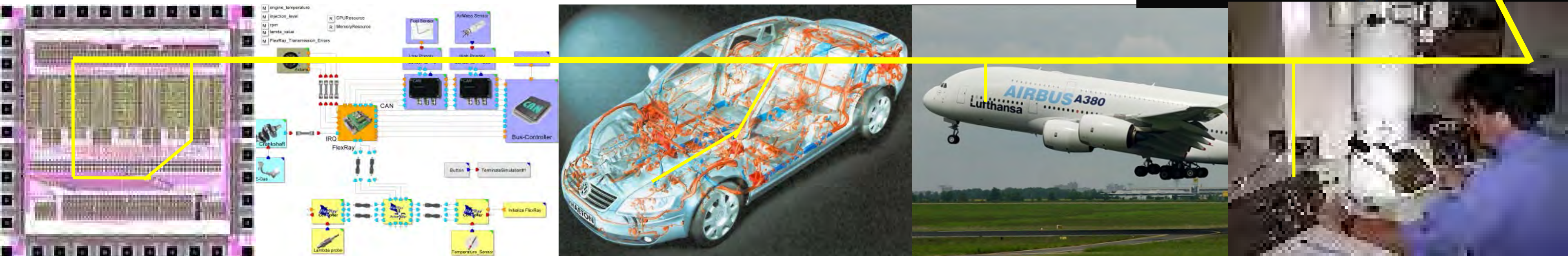

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