

# Generative Design and Automated Reasoning in the Design of Aerospace Systems

Jeff Heisserman  
Boeing

## GLOBAL PRODUCT DATA INTEROPERABILITY **SUMMIT** 2015



ELYSIUM

Darker Aerospace

NORTHROP GRUMMAN

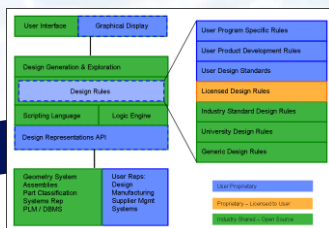
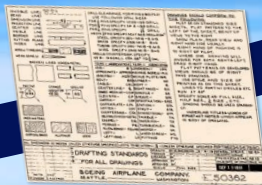
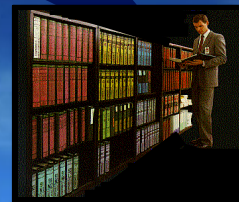
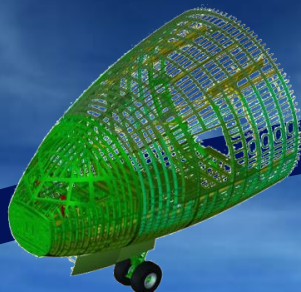
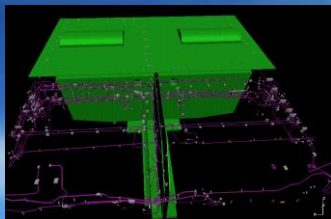
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BOEING



# Boeing Product Development – circa 1918

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Boeing Model C  
(1916, 56 built)

INVISIBLE LINE  
BEND LINE  
DIMENSION LINE  
PROJECTION LINE  
CENTER LINE  
VISIBLE LINE  
BORDER LINE  
CUTTING PLANE  
INDEX LINE

SCREW THREADS  
WOOD SCREW

BROKEN LINES WOOD & METAL

PARTS  
NO. 9165  
CHANGE INDICATOR  
SPEC. NO. 45

IRON & STEEL  
COPPER & BRASS  
ALUMINUM  
WOOD

DRILL CLEARANCE FOR PINS & BOLTS. USE FOLLOWING DRILL SIZES  
FOR PINS SPECIFY NO. 20-136-DRILL  
FOR PINS SPECIFY NO. 8-199-DRILL  
FOR PINS SPECIFY NO. 12-24-DRILL  
ABOVE PINS SPECIFY NEXT SIZE DRILL IN 64"  
STEEL SPECIFY .065-NO. 16-B.W.G.  
BRASS SPECIFY .0508-NO. 16-B.W.G.  
TUBING SPECIFY .065-NO. 16-B.W.G.  
WIRE SPECIFY .0508-NO. 16-B.W.G.  
DRILL & COUNTERSINK SPECIFY:  
NO. 8-199-DRILL C.S.K. 82° TO 1/8" DIA.

TERM	ABBREVIATION	TERM	ABBREVIATION
AND-		LONGERON-	LN.
APPROXIMATE-	APPROX.	MACHINE SCREW-M.S.	
ASSEMBLY-		ASSY NICKLE PLATE-NIP	
BOLT-		BOL NUMBER-	NR
CABLE-		COL RIGHT-	R.
CENTER LINE-	C.	RIGHT HAND-	RH.
CHANGE ORDER NO-	COM.	SHACKLE-	SH.
CLEVIS PIN-	C.P.	SHEAVE-	SHY.
COPPER-	COR.	SPECIFICATION-SPEC.	
COPPER PLATE-	C.P.L.	STATION-	STA.
COTTER-	COT.	STRUT-	STR.
COUNTERSINK-	C.S.K.	SYMMETRICAL-	SYN.
COLD ROLLED STEEL-CRSTL.		THINBLE-	TH.
ENAMEL-	ENL.	TAPER PIN-	T.P.
FERRULE-	FRL.	TURNBUCKLE-	TB.
FILLER & WASHN-	FLLR & WASHN-	WASHER-	WA.
LEFT-	L.	WOOD SCREW-	W.S.
LEFT HAND-	L.H.	FITTING	FTG.

DRAWINGS SHOULD CONFORM TO THE FOLLOWING.  
MUST BE ON STANDARD SIZE SHEETS, FLAT PATTERN TO THE LEFT OF THE SHEET, BENT UP VIEWS TO THE RIGHT.  
SHOW PLAN, REAR VIEW AND RIGHT HAND SIDE USUALLY.  
RIGHT HAND OF MACHINE IS TO RIGHT OF PILOT.  
WHERE ONE DRAWING WILL ANSWER FOR BOTH RIGHT & LEFT DRAW RIGHT HAND.  
FLAT PATTERNS OR DEVELOPED VIEWS SHOULD BE OF RIGHT HAND DRAWINGS.  
USE STYLE AND SIZE OF PRINTING AS ON THIS SHEET.  
RUN AT 45°  
SPECIFY SCALE AS: FULL SIZE, HALF SIZE, 1/4 SIZE, ETC.  
SHADING SHOULD BE USED SPARINGLY.  
UNDERLINE TITLES & WORDS OF IMPORTANT NOTES WHICH APPEAR IN BODY OF DRAWING.

ALL DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED

DRAFTING STANDARDS  
FOR ALL DRAWINGS

BOEING SEATTLE, AIRPLANE COMPANY, WASHINGTON

DRAWN BY R. BIERENS  
CHECKED BY  
APPROVED BY  
APPROVED BY  
SCALE FULL SIZE

PART NO. 1234567890  
MATERIAL SPRUCE  
FINISH NONE  
FINISH FILL & VAC  
ISSUE DATE OF PRINT ISSUE NO.  
SEP 19 1918

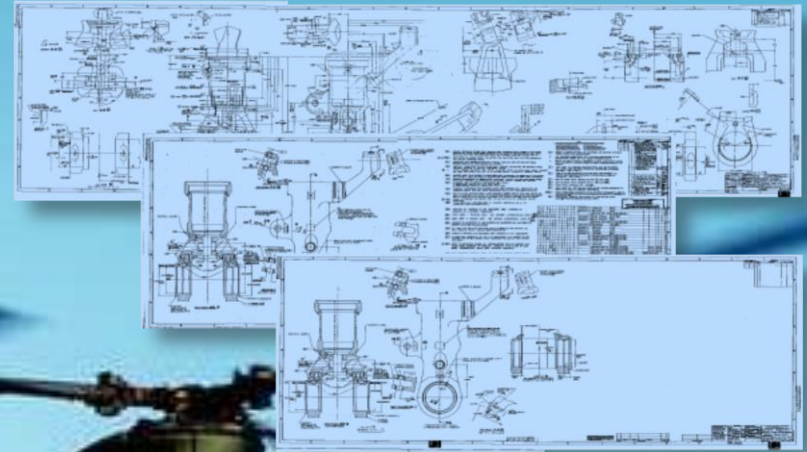
50362

# Boeing Product Development – 1970s

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9000 pages of part standards  
8600 part attribute rules  
475 BAC process specs

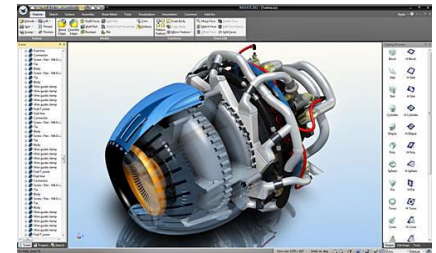
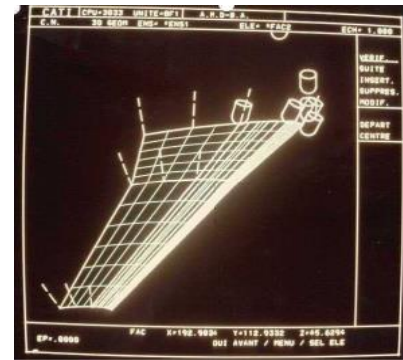
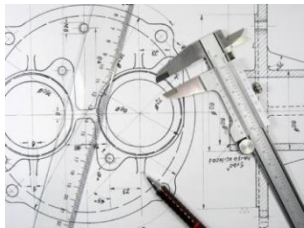


**40 billion**  
part numbers

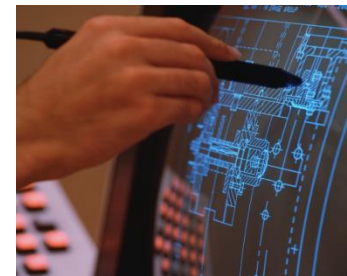
# Evolution of Product Design

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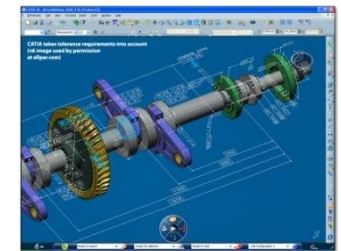
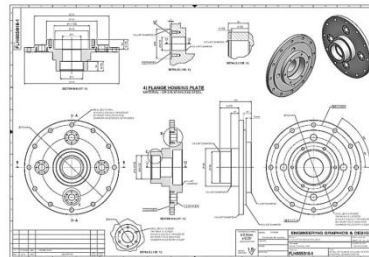
- Drawings
- Lots of paper



- Digital designs
- Parametric modeling
- Model based definition
- 3D GD&T
- Product Standards Data
- PLM, PDM, ERP, MES
- Virtual Manufacturing



- Digital drawings
- Early solid modeling
- Data entry systems



1960

1970

1980

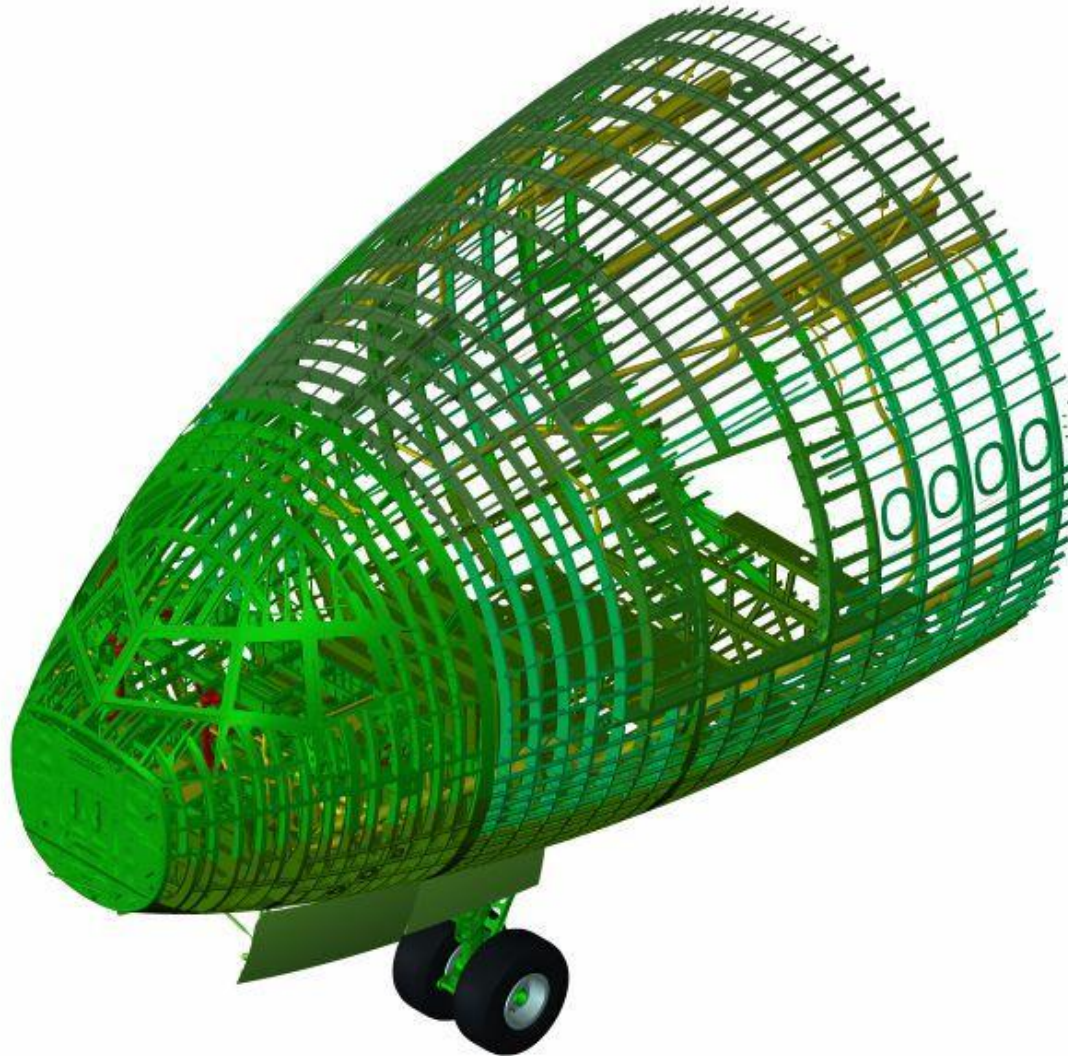
1990

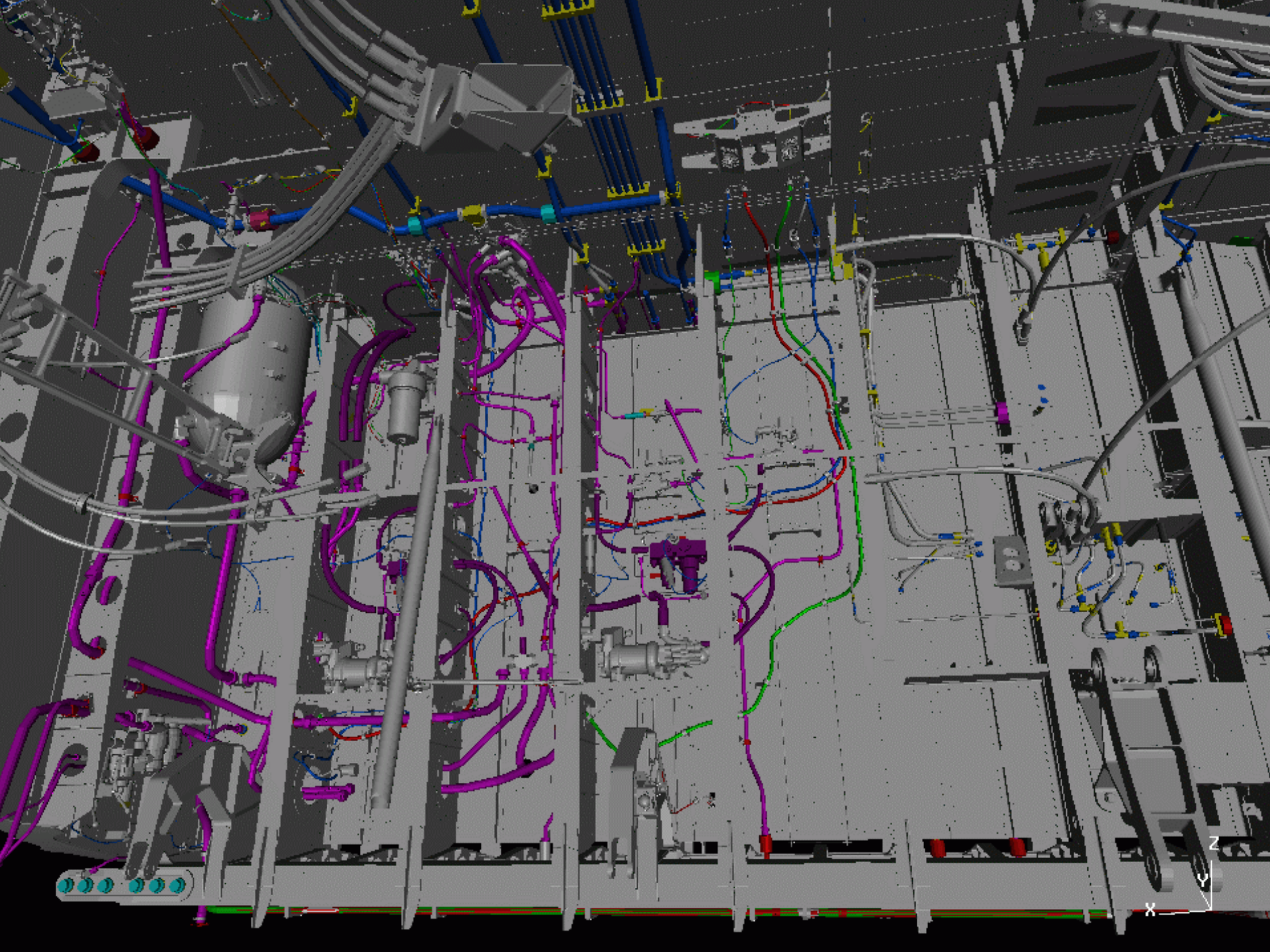
2000

2010

# Boeing Product Development – 1990s

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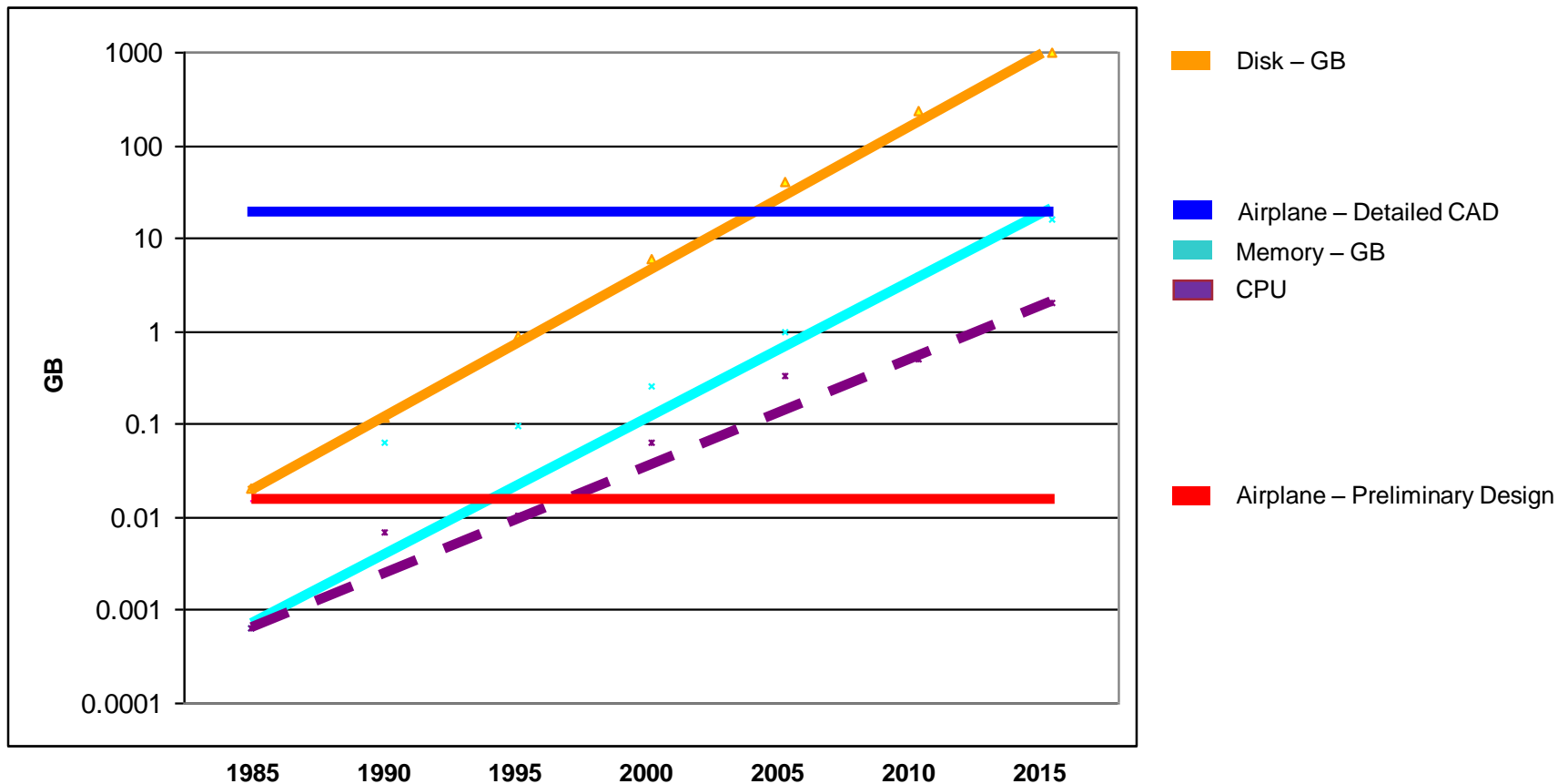




# Desktop Computational Capacity

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or Moore's Law as it applies to aircraft design



# Computational Design

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We want to

- Automate repetitive work
- Develop better products within shorter cycle times
- Reduce development costs



We are facing huge engineering challenges

- People are creative and flexible, but expensive
- Computers are systematic, tireless, thorough, and cheap
- ... and we just don't have enough engineers

We want to create innovative designs  
that we just can't create otherwise



# Computational Design

Global Product Data Interoperability Summit | 2015

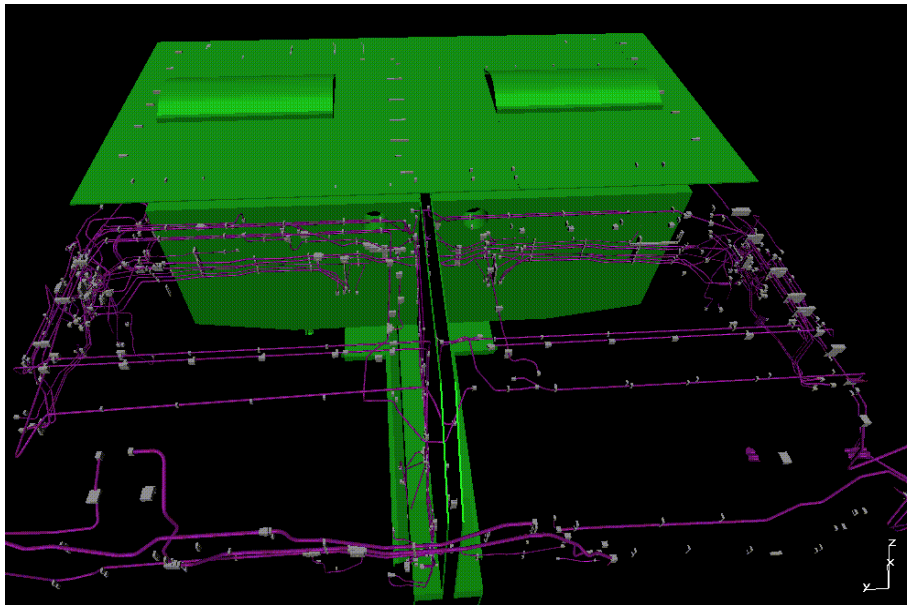
- Knowledge-Based Engineering (KBE)
  - the tools and technologies for encoding engineering knowledge and methods in software to analyze and generate aircraft, component, tooling and other designs
- Generative Design
  - automated reasoning with interactive and automated design methods - based on the concepts of shape grammars and spatial grammars - that are used for generating designs and exploring spaces (languages) of designs.
- By encoding our knowledge
  - in modular, flexible design rules
  - applying them to generate and check our designs
  - use our computers as intelligent design assistants
  - leaving the more difficult - and more interesting - problems to our engineers

# Genesis / KIRTS

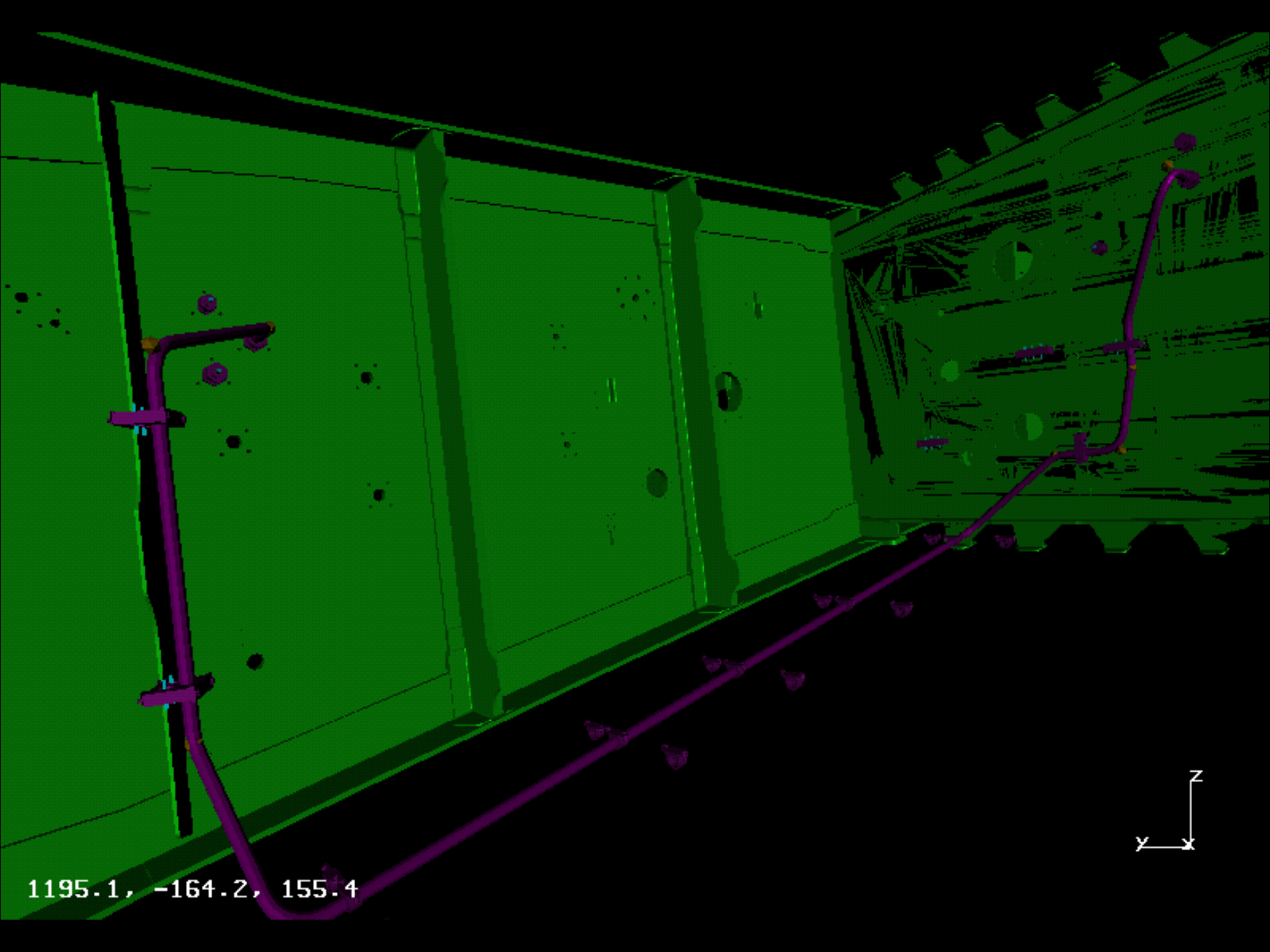
## Knowledge-based Integrated Routing Tool for Systems

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- used for the design of aircraft systems tubes, pipes, ducts, hoses, cables and bundles, including clamps, clamp blocks, fittings
- for hydraulic systems, fuels, cabin air, emergency oxygen, smoke detection, fire suppression, fresh water, gray water, sewer
- contains design rules for engineering, manufacturing, fabrication and maintenance



767-400 Hydraulic Systems  
main landing gear bay



1195.1, -164.2, 155.4

# A Genesis / KIRTS Design Rule

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```
condition(tube1,  
  'Tube has no geometry.').
```

```
lhs(tube1, [Tube], [Part1, Part2]):-  
  schematic_tube_connections(Tube, Part1, Part2),  
  in_context(Tube),  
  not occurrence_has_geometry(Tube),  
  occurrence_has_geometry(Part1),  
  occurrence_has_geometry(Part2).
```

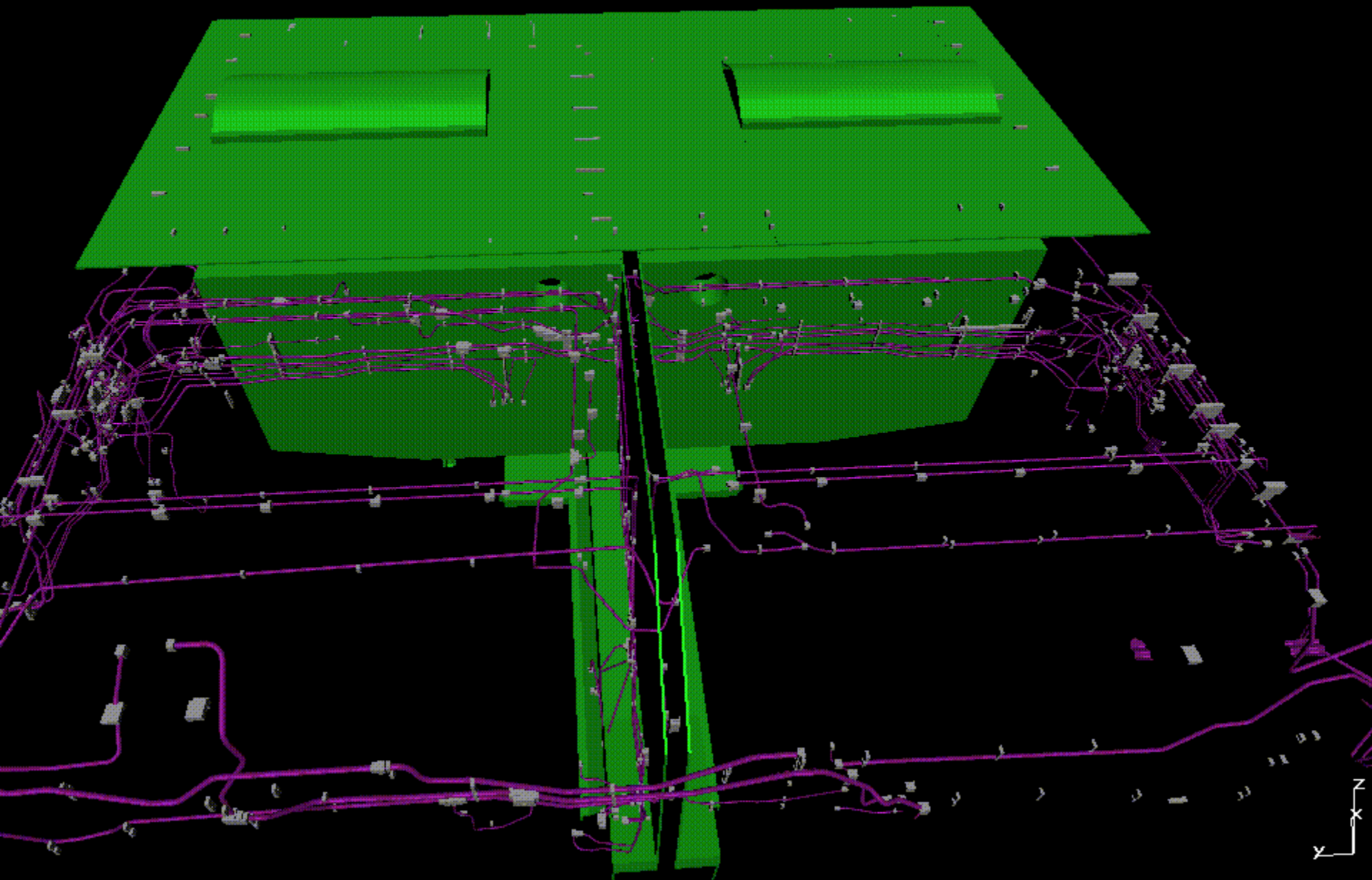
```
description(tube1,  
  'Create a tube and its fittings.').
```

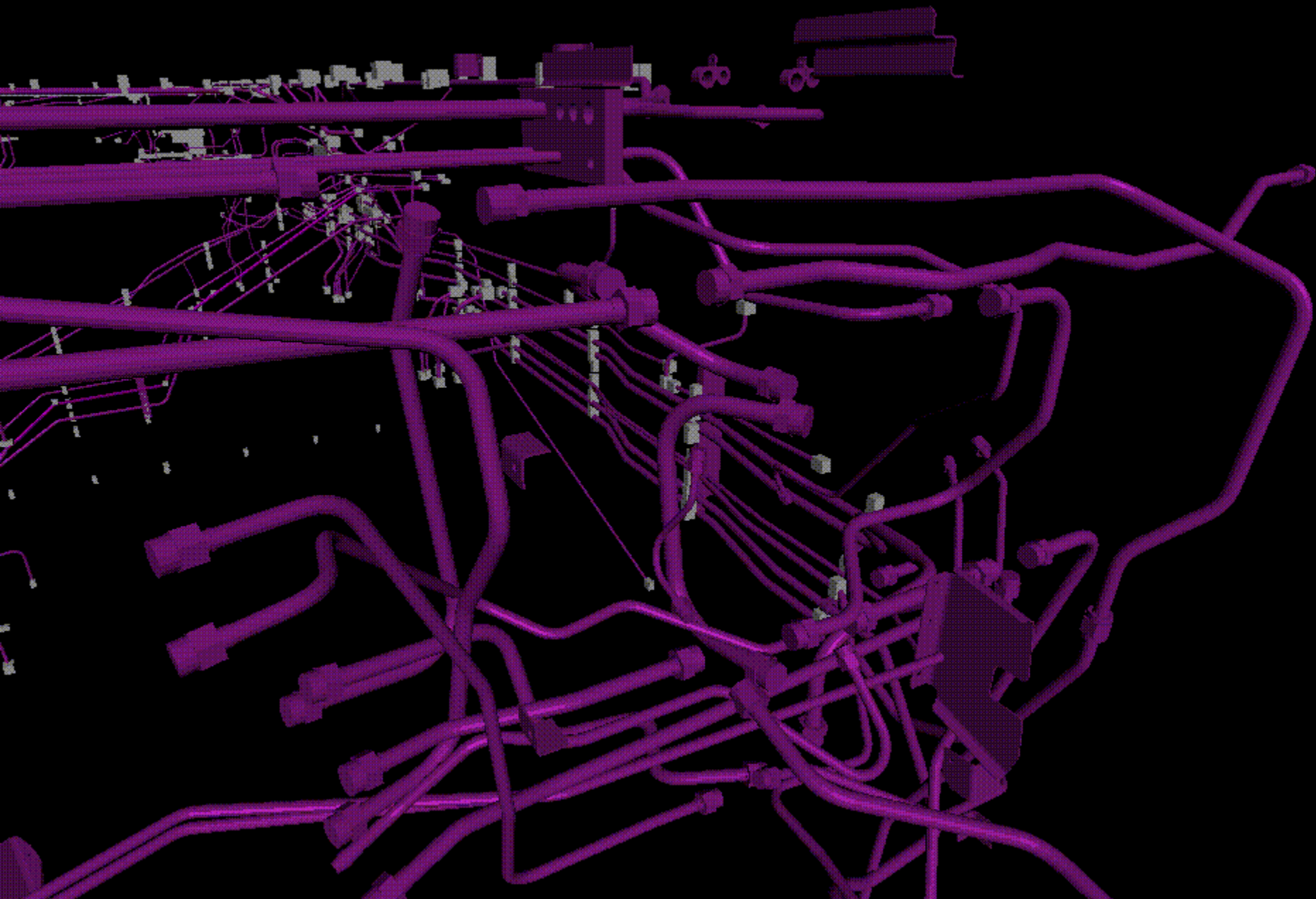
```
rhs(tube1, [Tube]):-  
  make_tube(Tube).
```

# Logical Reasoning about Designs

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- **Axioms / base representations**
  - solids & assemblies
  - part type classifications
  - part interfaces
  - system schematics
- **First-order logic**
  - map from design rules to base representations
- **Goal clauses**
  - specify design conditions





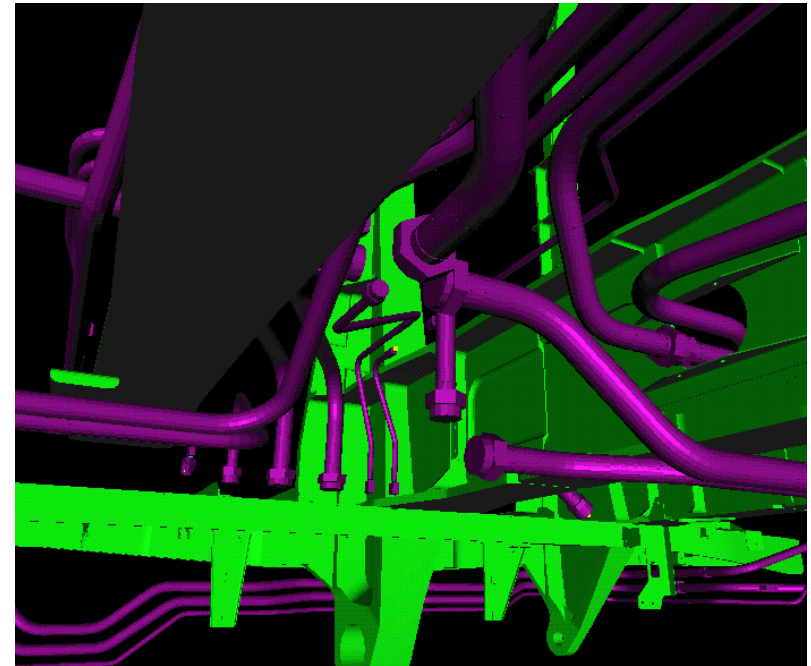
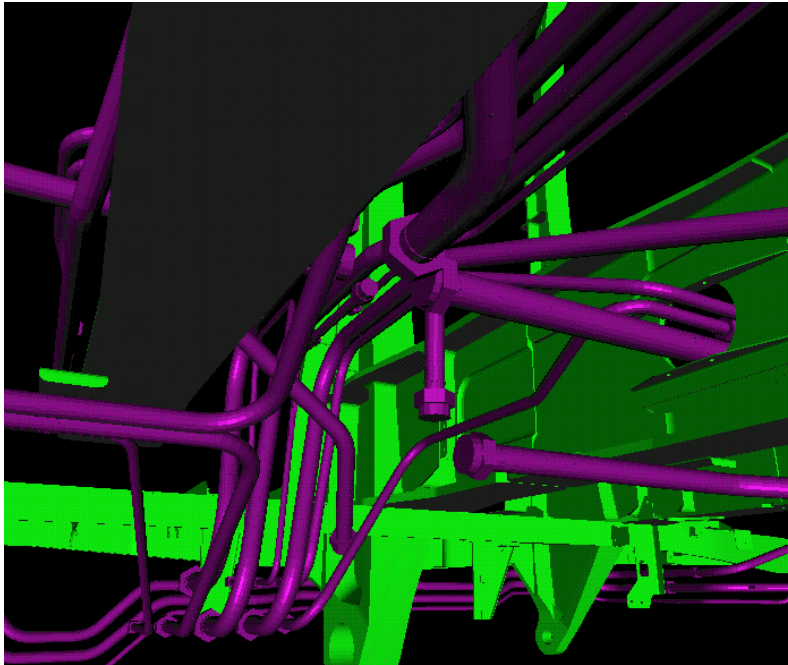
# Design Generation & Exploration

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- **Design generation**
  - interactive generation and modification using design rules
  - automated generation of detailed designs
- **Design checking**
  - correctness and consistency checking
  - automated analysis
  - integrated simulation
- **Exploring spaces of designs**
  - automated generation of alternative designs
  - design iteration and quality evaluation
  - design comparison and merging

# Comparing Designs in Genesis/KIRTS

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# From Research to Production

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## Carnegie Mellon University / Queen Anne Houses

- Representing 3D polyhedral solids
- Logical reasoning
- Parametric shape rules
- Simple design generation

## Boeing / Aircraft Systems

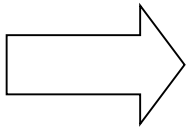
- Representing 3D solids, assemblies, part classes, ports, function
- Parametric shape (plus) rules
- Interactive rule application & automated generation
- Simple design evaluation & exploration
- Representing design variants (alternative) designs
- Fast interference and systems separation checking
- Large scale, in-context design
- Comparing designs

# Open Source Computational Design

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What we need is a *community effort* to build computational design tools that are

- high quality, robust and innovative
- interoperable with CAD/CAM/PDM systems
- embeddable in custom applications, analysis and optimization tools
- usable by everyone



Free and open source software



# Open Source Computational Design

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## Why would Boeing want to develop a design system as Open Source?

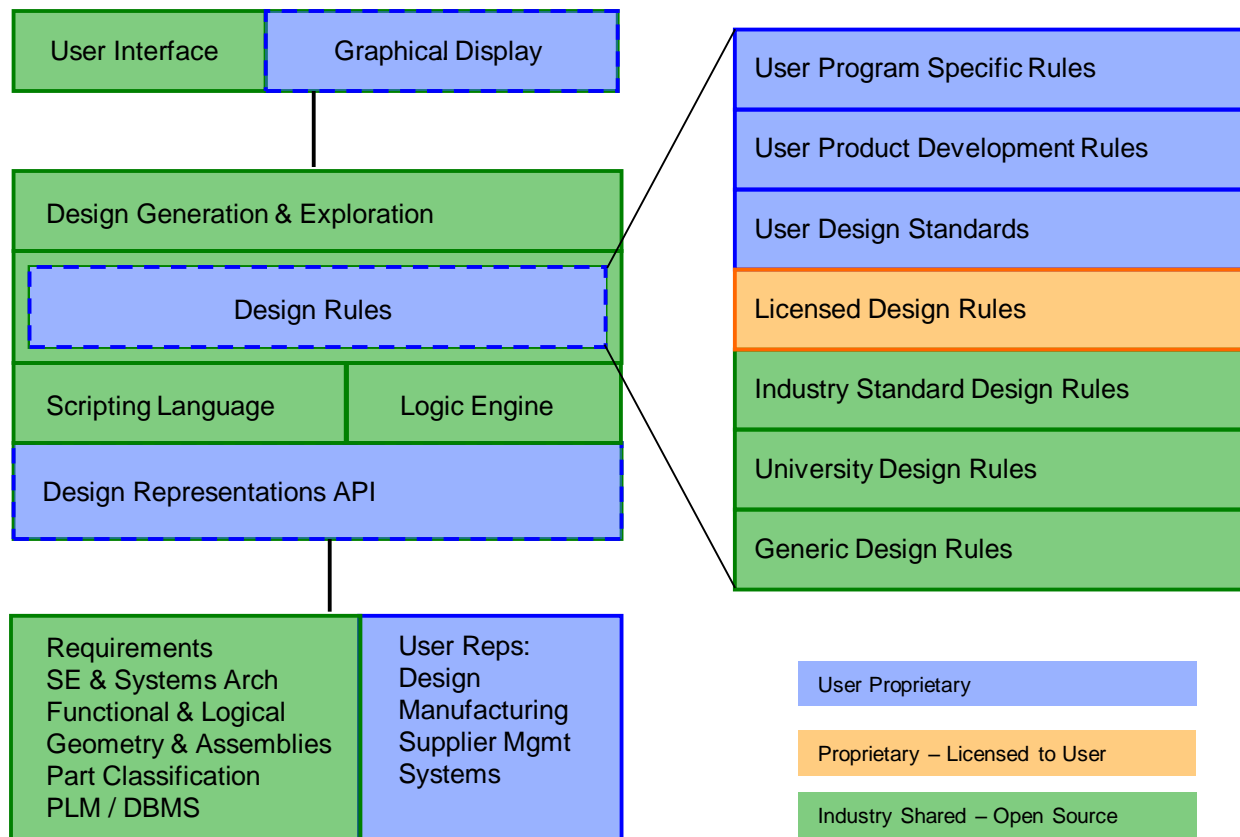
### We want to

- develop a robust, long lived system that can be used to develop multiple generations of airplanes and aerospace products
- share the costs of developing and maintaining the system
- move to a standard, neutral knowledge representation
- enable sharing of design rules, e.g. from NASA, FAA, universities
- encourage collaboration with universities, government labs and industry to develop state-of-the-art capabilities
  - speed technology transfer into Boeing
  - speed the application of new technologies to Boeing products
  - supports research collaboration with Boeing
  - facilitate hiring of outstanding engineers into Boeing

# Open Source Software Knowledge-Based Engineering

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## Architecture and User Scenario



- We use a modular architecture, with
  - modules that are shared open source
  - proprietary modules that are not shared
- We choose an open source license that allows users to use open source modules with proprietary modules – without having to share the proprietary modules
- Users can decide what design rules to share and what to keep to themselves
- Users can develop proprietary capabilities to augment the open source capabilities

# Computational Design

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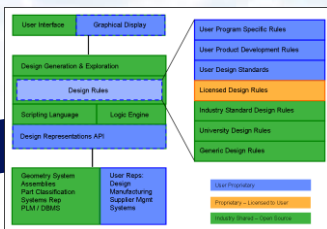
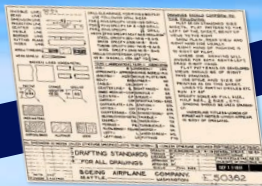
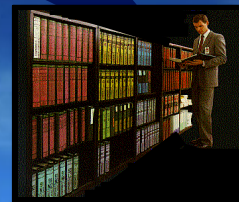
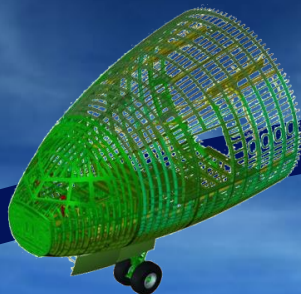
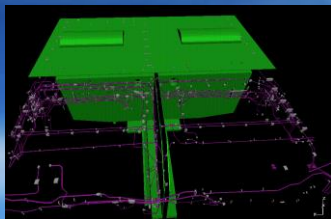
## Our Engineering Grand Challenge:

Construct, apply and share engineering knowledge

- in an active, computational form
- able to analyze designs
- able to synthesize and
- able to optimize designs
- with the knowledge independent of the design system

... in other words

Global Product **Knowledge** Interoperability



# Credits

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## OSSKBE

- Jeff Heisserman
- Chris Esposito
- Bill Brown
- Tom Velte

## Genesis / KIRTS

- Jeff Heisserman
- Sean Callahan
- Raju Mattikalli
- Mike Drumheller
- Jan Vandenbrande
- Virgil Bourassa
- Ian Angus
- Bob Abarbanel
- Fred Holt
- Carl Pearson
- Greg Green
- Bob Perry
- Steve Cheng
- Harry George
- Dat Tran
- Bill McClay
- Mark Williams
- Eric Haberman
- John Kershinar
- Matt McMullen
- Mary Hopwood
- Frank Gosson
- Mike Galuska
- Britt Thompson
- Kelly Rogerson
- Rajendra Deonarine
- David Kamihara
- Mary McCartor
- Fred Aboosaidi
- Bernard Thompson
- Steven Wright
- ... and more

