Development of Design Supports for Functionally Integrated Aero-engine Structures

Thesis accessible https://research.chalmers.se/publication/510065

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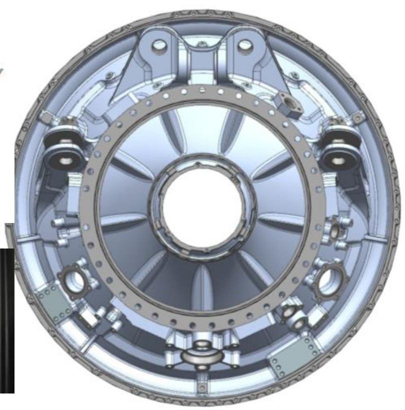
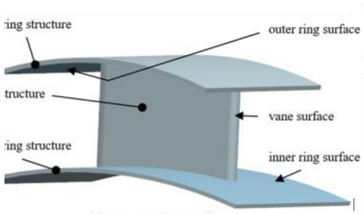
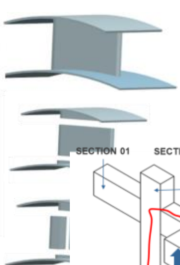
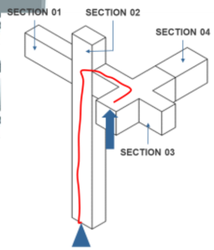
09 Oct 2019

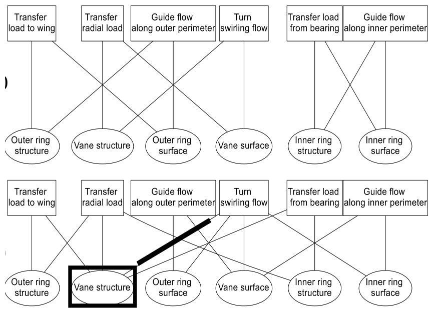


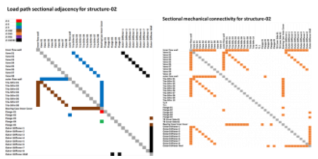


Vane and sections









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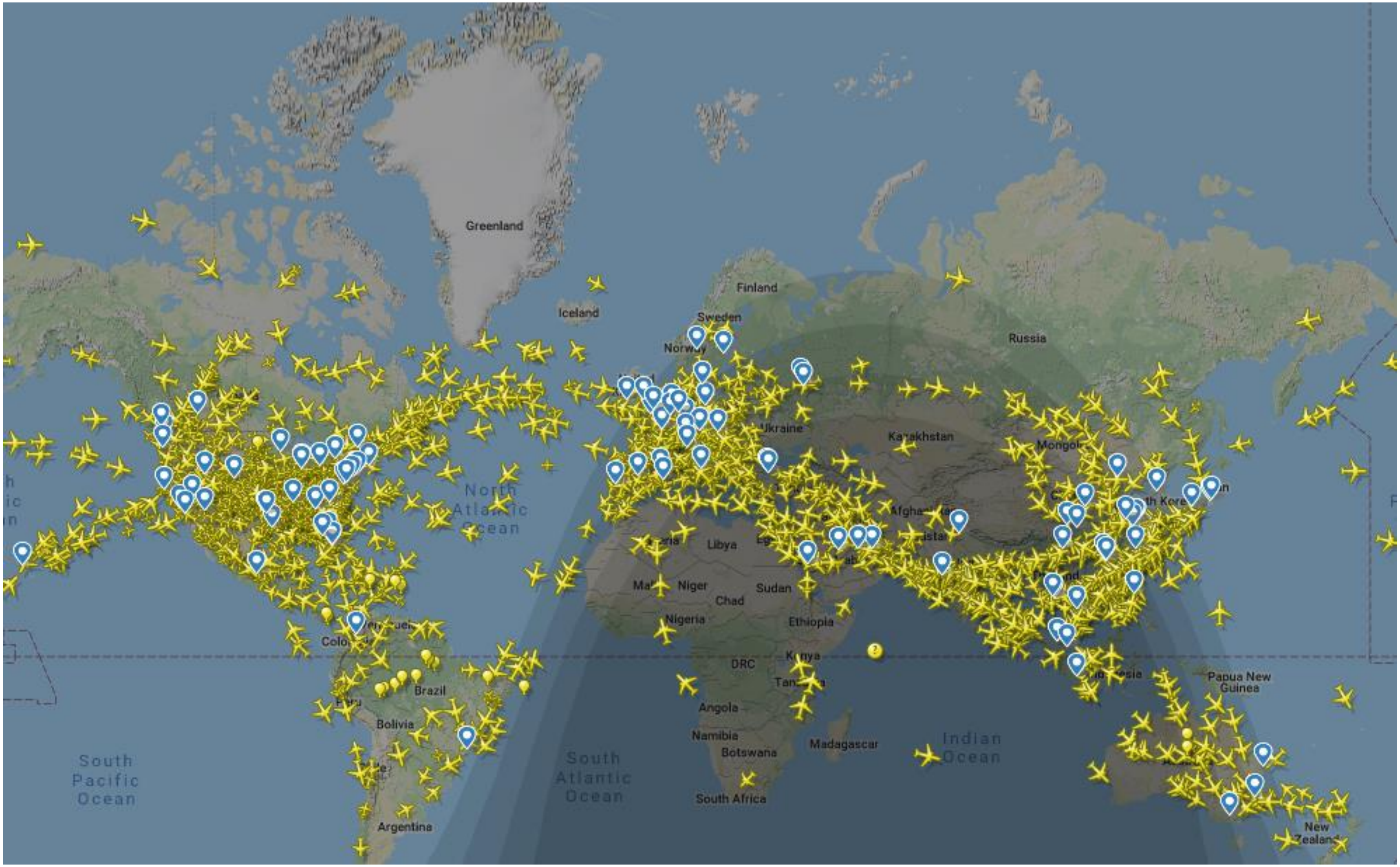
Global Air Traffic



Flight Radar, 21 May 2018. https://www.flightradar24.com/8.67;

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Commercial Aviation

- Commercial air-traffic continues to rise
  - 7% (300 million) more passengers in 2017 from 2016 §
- Demands on aviation
  - Dramatically reduced emissions
  - Enhanced safety
  - Reduced fuel consumptions
- Novel designs or improving existing designs
- Effective design and development important

§ ICAO (2017) The World of Air Transport in 2017 [Web Page]. Available at: https://www.icao.int/annual-report-2017/Pages/the-world-of-air-transport-in-2017.aspx (Accessed: 17 August 2018).

Project Context

- The Design for Performance Projects (DFP)
  - VINNOVA ; NFFP6 and NFFP7
- Collaboration between
  - GKN Aerospace
  - Chalmers
- Focus on GKN developed engine structures
- Demands from both industrial and academic perspective

Agenda

- Background
- Research Questions (RQ)
- Research progression by addressing RQs
- Summary
- Conclusion and future work

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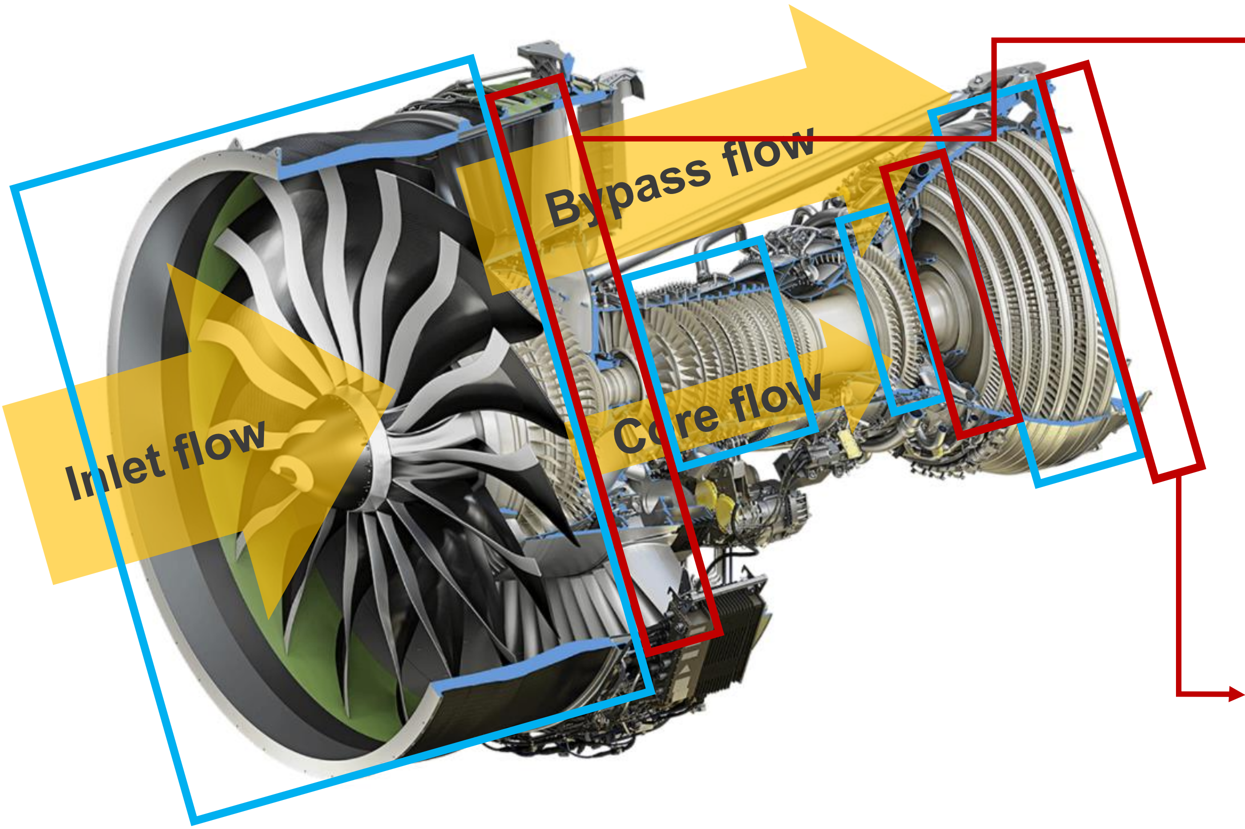
The Aero-engine and its Structures



- Typically located at module (compressors/turbines) interfaces
- Transfer mechanical load and direct core-gas/air flow
- Single piece castings or weld fabricated

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Engine Structures Development

- Incremental and experience based development
  - Difficult to see which functions are fulfilled where, and how
- Problems for new designs and improving existing ones
  - No existing methods to visualize and evaluate functional fulfilment
- To improve design, understanding is needed about:
  - Structure’s effects on the system
  - Structure’s adaptation to the system
- New methods are necessary
  - For modeling and evaluating design information

Research Questions

A

How does the product behave in the system?

RQ 1

What are the effects of engine structures on the performance of the engine?

B

How does the product adapt to the system?

RQ 2

What characterizes the architecture of the product and how to represent the architecture?

RQ 3

How can the architectural insights derived for the product be utilized in initial design stages?

RQ 4

How can a quantitative metric be created for the architecture so that comparison among products of the same class is made easier?

Case for Improving Engine Structures Design

- Structures design highly dependent on system inputs

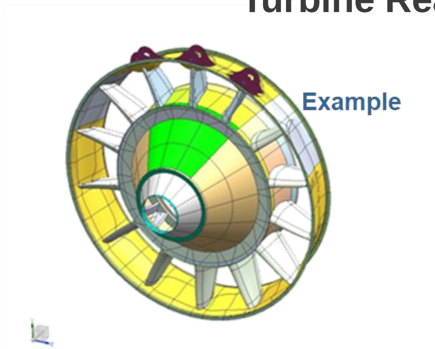
- Worth spending time with the design of these structures?

RQ1

What are the effects of engine structures on the performance of the engine?

Study Engine Operation & Pressure Drop

Turbine Rear Structure (TRS)

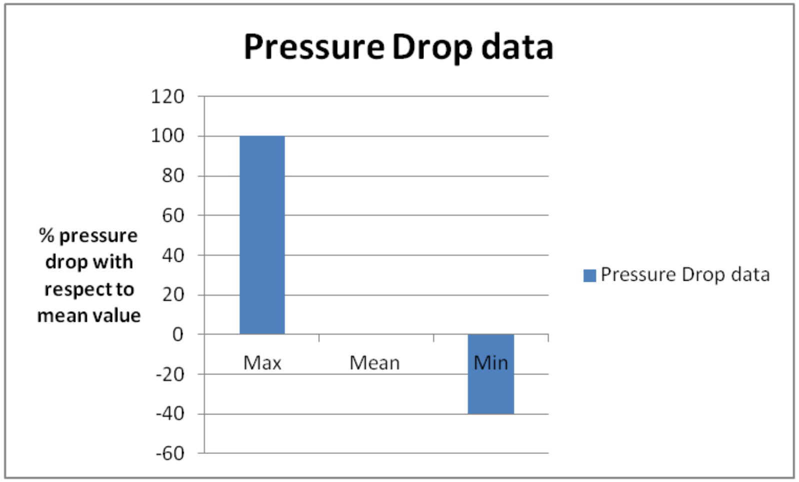


Aerodynamically Good Design wrt Pressure Drop :

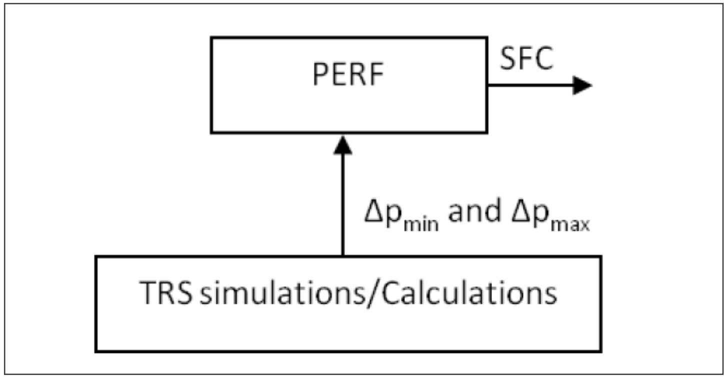
Can be poor from Weight or Lifing perspective

Aerodynamically Poor Design wrt Pressure Drop:

Can be good from Weight or Lifing perspective



- Take pressure drop ranges
- Couple it to SFC calculation



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Engine operation & Pressure Drop

- Good design can save SFC by about 0.9%
- 0.9%; not too big?

Significance of Good Design

- Can save about 900,000 USD in fuel costs/year/airline
  - BA fleet of 34 747s, assuming 1200 hour cruise/year/aircraft
  - Influence from only one component
- Component operation is important: design is important

€ $

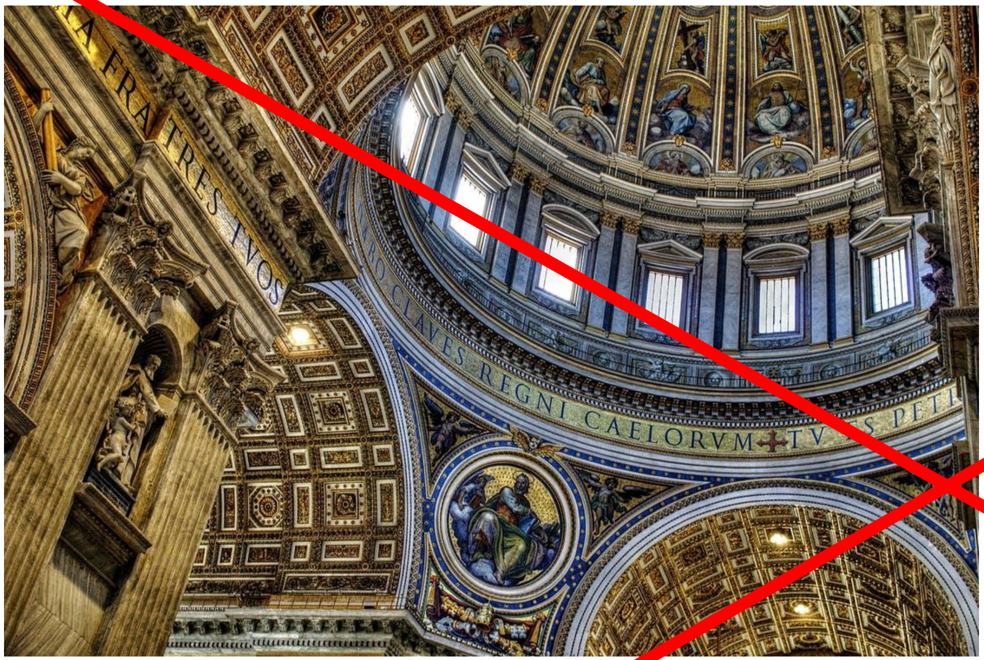
How to Improve Design ?

- Ultimately improves engine (system) performance
- Product Architecture
- Complexity Studies

RQ2

What characterizes the architecture of the product and how to represent the architecture?

Architecture



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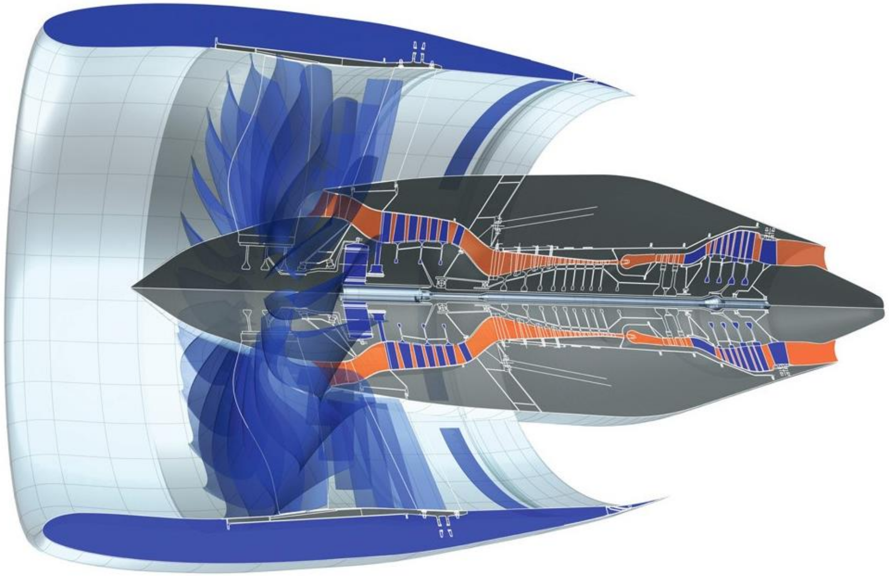
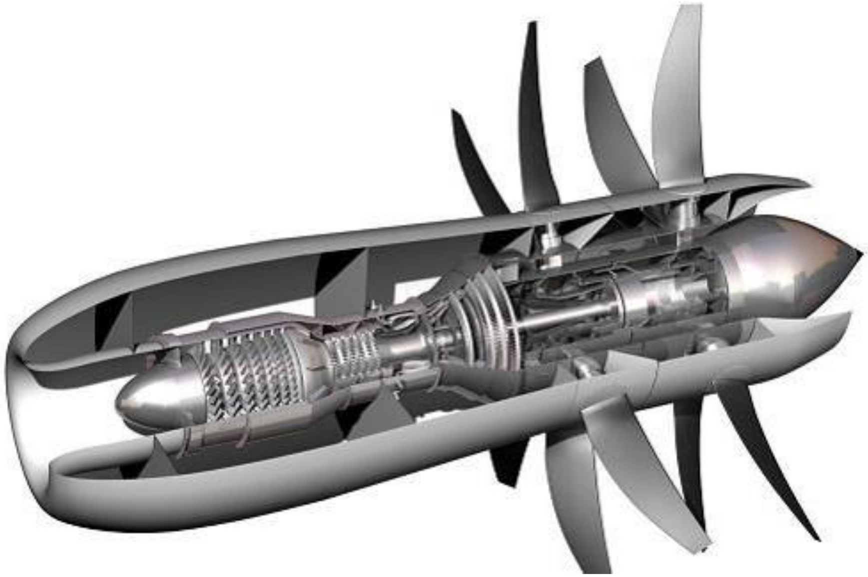
Product Architecture

- Allocation of functional elements to structural elements
- In general, answers the question:
  - How is the product organised so as to satisfy its functions?





Images from:
ENOVAL Ultra High Bypass Ratio Engines, Technolgy Brocure, July 2018
Southampton.ac.uk. (2019).Available at: https://www.southampton.ac.uk/antc/projects/ror.page [Accessed 1 Jun. 2019]

Modular and Integrated Architecture

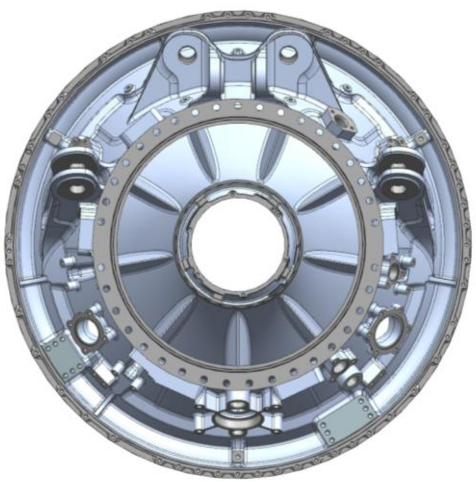
provide lighting = LIGHT BULB

provide support = STEEL STAND

provide power = ELECTRIC CABLE & HOUSING

each function provided by a *module*

Modular Architecture

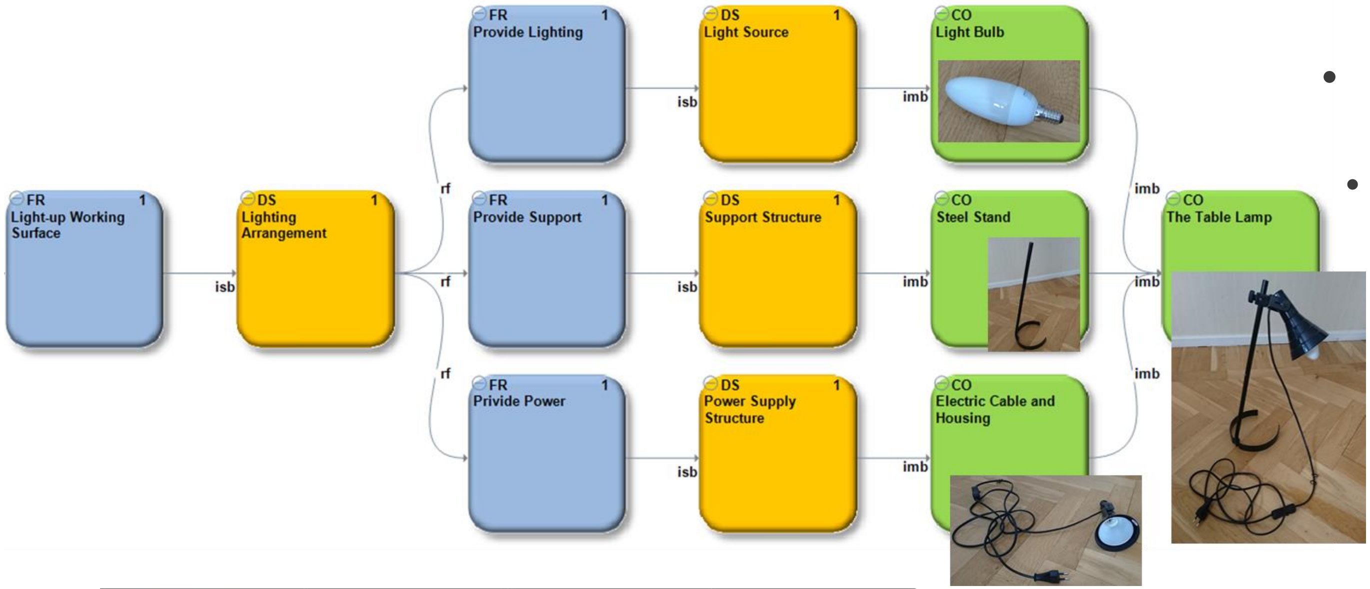


What if all functions are satisfied by one single component?

every function provided by a *single, monolithic structure*

Integrated Architecture

Architecture Representations



- **Function–Means Tree**
  - **Problem-Solution map**

	Light Source 	Support Structure 	Power supply structure 
Light Source 		0	1
Support Structure 	0		1
Power supply structure 	1	1	

- **Design Structure Matrix**
  - **Solution-Solution map**

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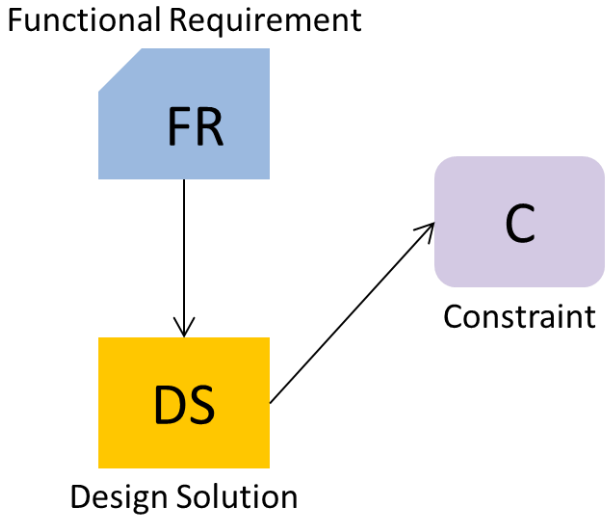
EF-M for Functionally Integrated Structures

- Sections concept
  - Identifiable regions, satisfying functions
- Sections considered the same as design solution



The Enhanced Function-Means Tree

Concept	Corresponding EF-M Terminology
Sections	Design Solution

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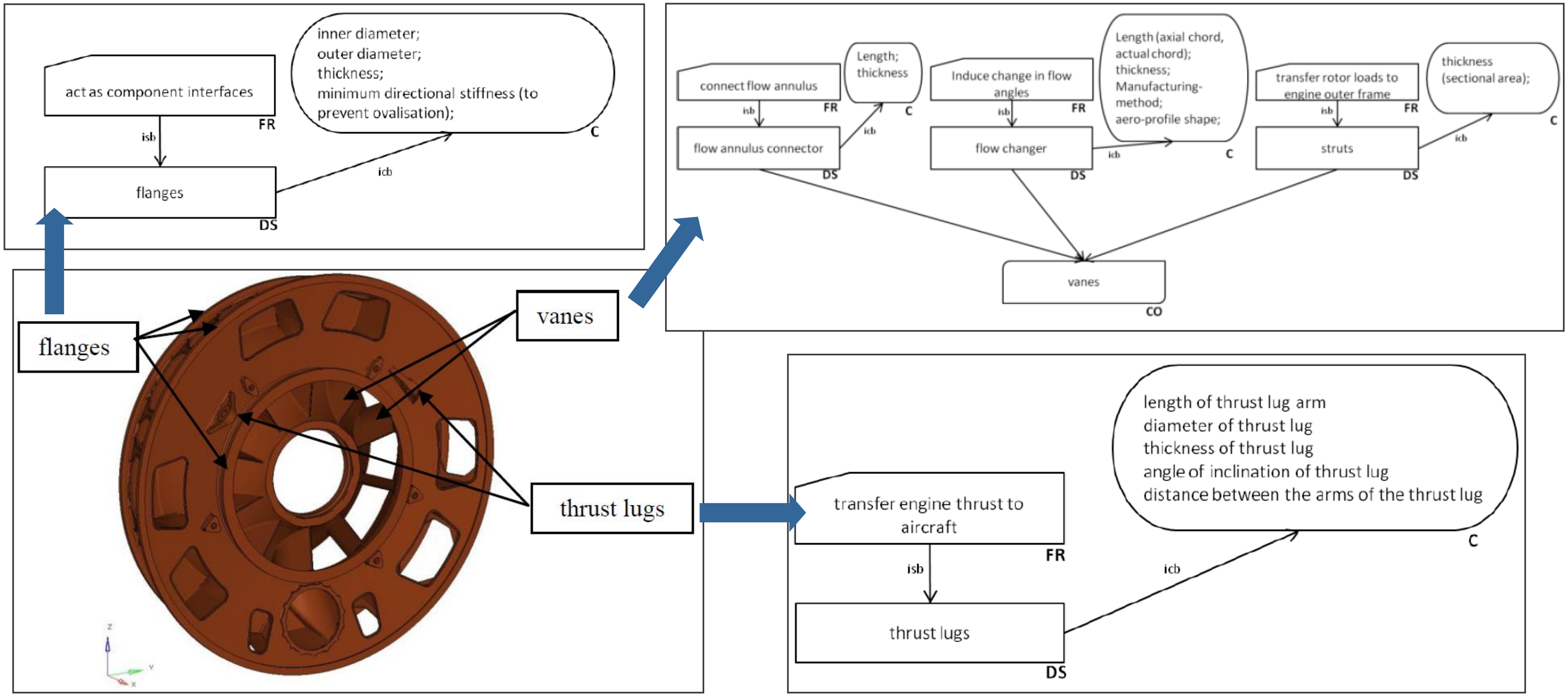
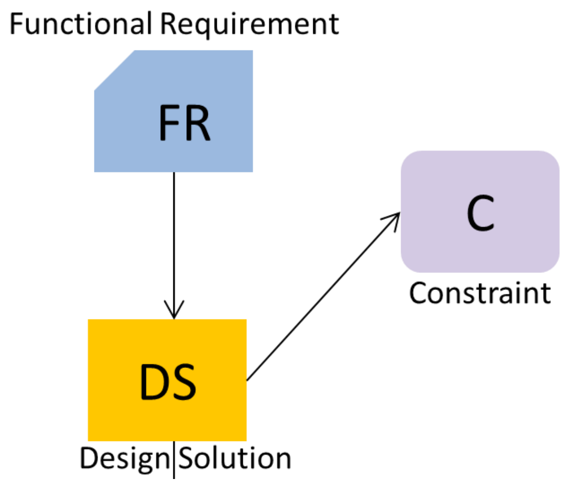
Architecture for Engine Structures



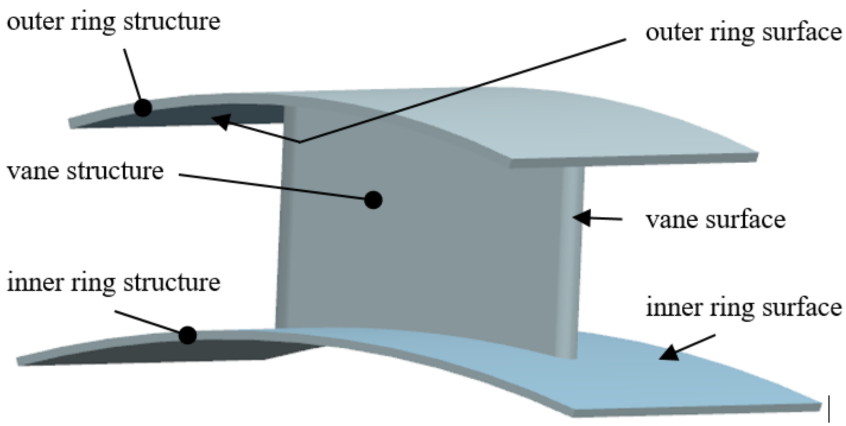
Good for one structure; can manufacturing options be included?

Manufacturing Options and EF-M Tree

- Manuf. segments same as CO (component)

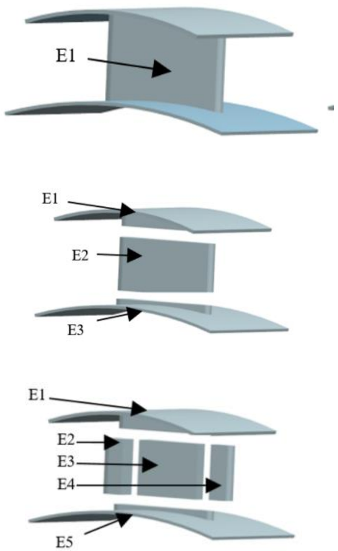


EF-M Tree



Vane and sections

Manuf. Options



Concept	Corresponding EF-M terminology
Sections	Design Solution
Manufactured Segment	CO (component)

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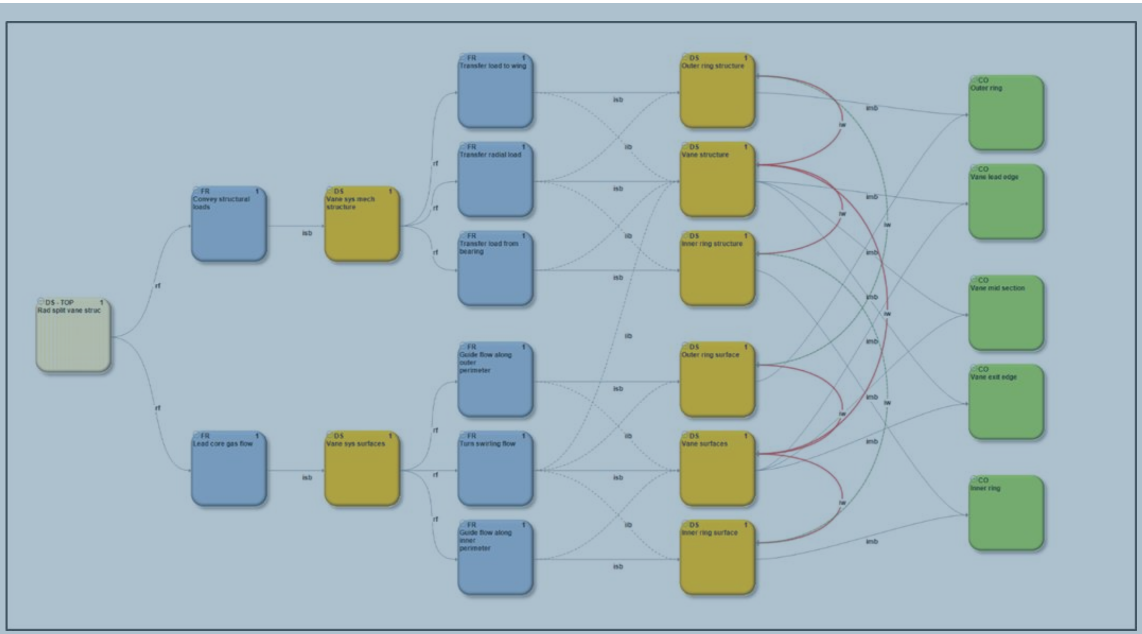
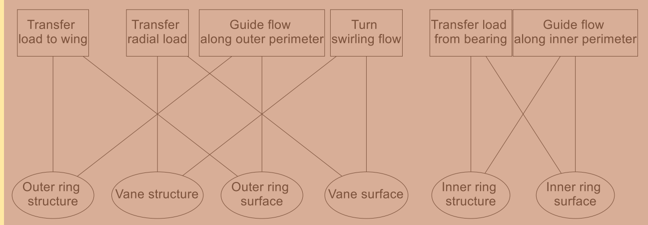
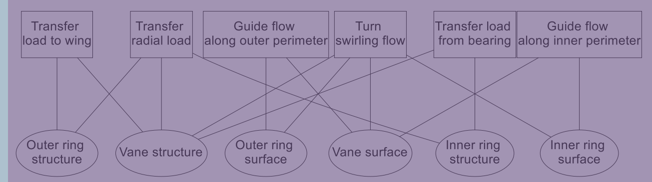
Graphs from Set Theory and EF-M Tree

{ F1, F2, …, Fn } → { E1, E2, …, En } → { S1, S2, …, Sn }

Functions **Segments** **Sections**



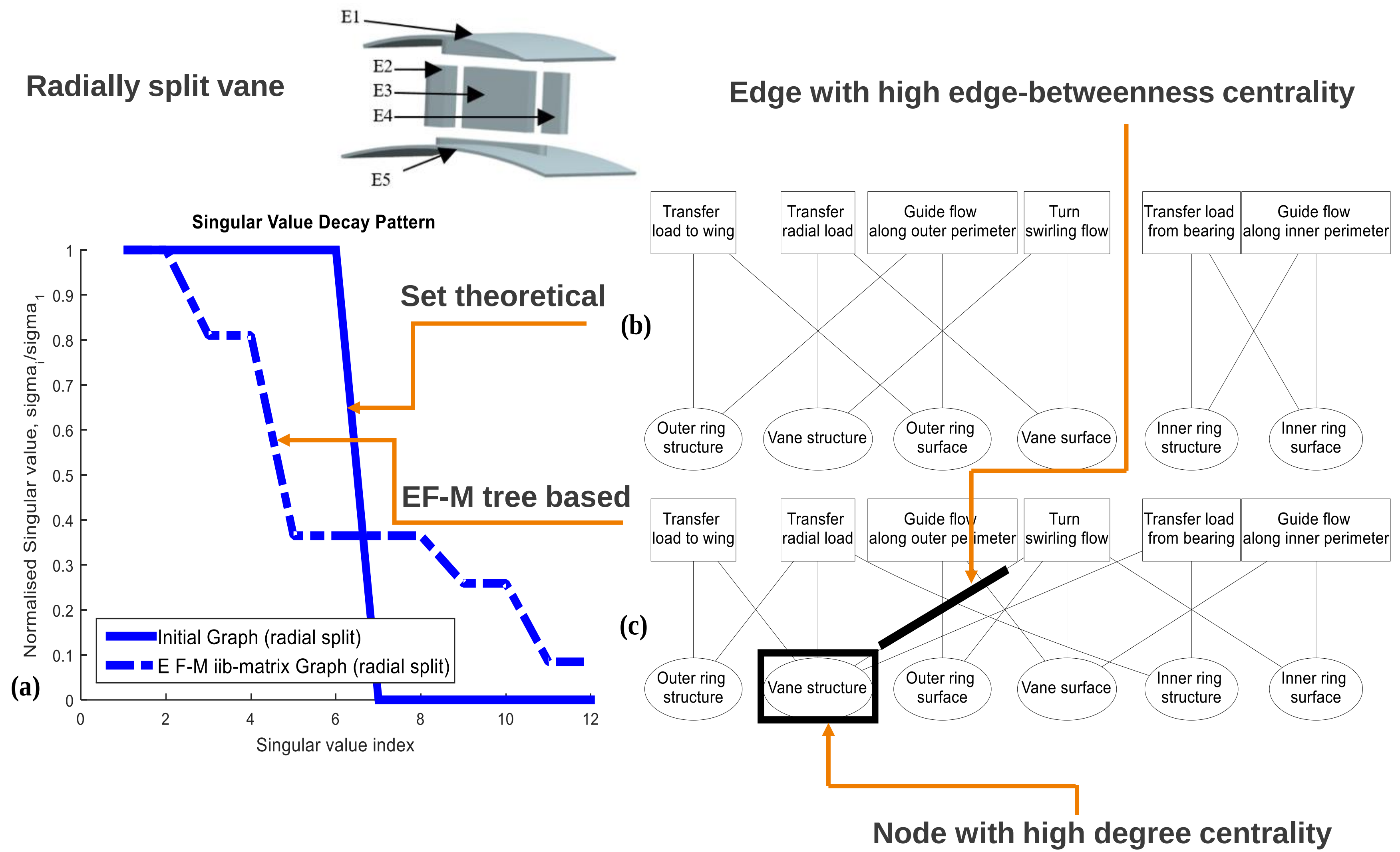




Inferences Based on Properties of Graphs

- Most “connected” sections
  - Degree centrality
- Most “traversed” relations
  - Edge-betweenness centrality
- Function-section “groupings”
  - SVD decay patterns

Inferences Based on Properties of Graphs



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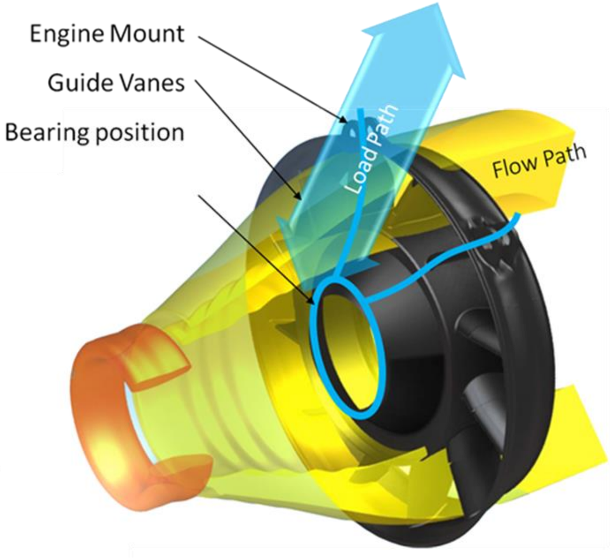
Insights on Engine Structures Architecture

- Sections useful in describing the structure
- Aspects of architecture in terms of primary functions
  - Provision of a mechanical load path
  - Provision of a gas flow path

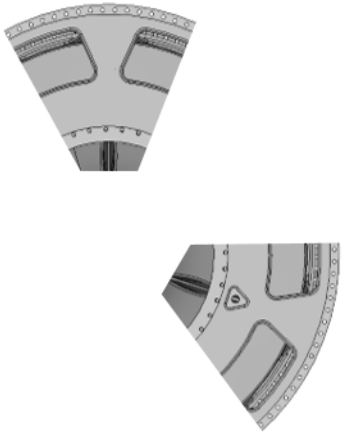


Practical uses of these architectural insights?

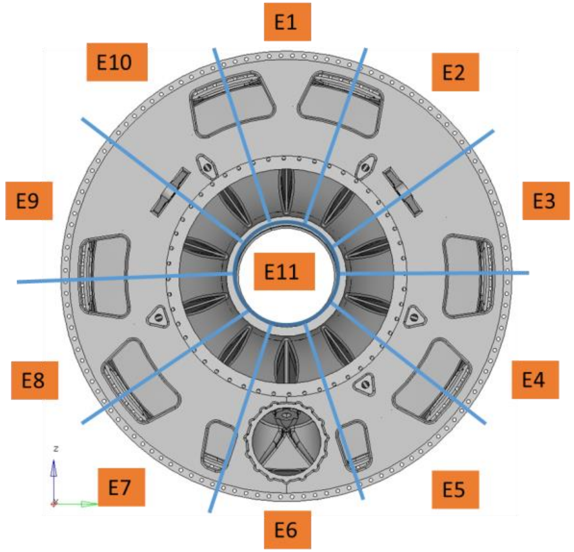
RQ3

How can the architectural insights derived for the product be utilized in initial design stages?

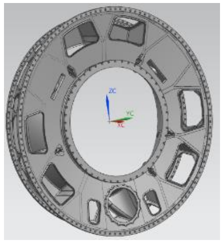
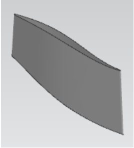
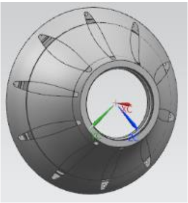
Complete Engine Structure & Manuf. Options



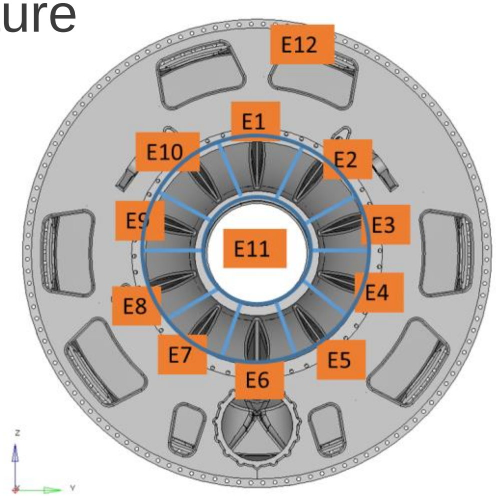
Sector Casts



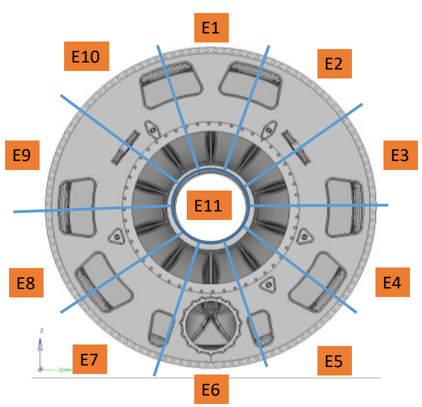
Manufacturing Options for a Complete Engine Structure

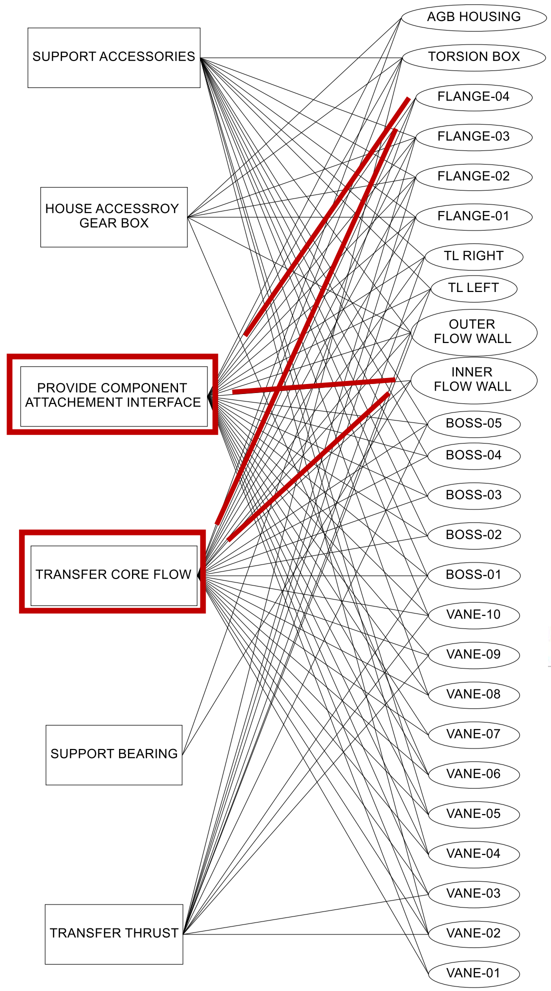
Separate Casts

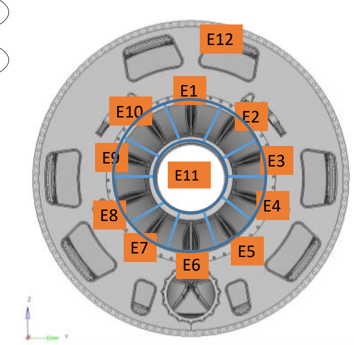


Architecture and Segmenting Options

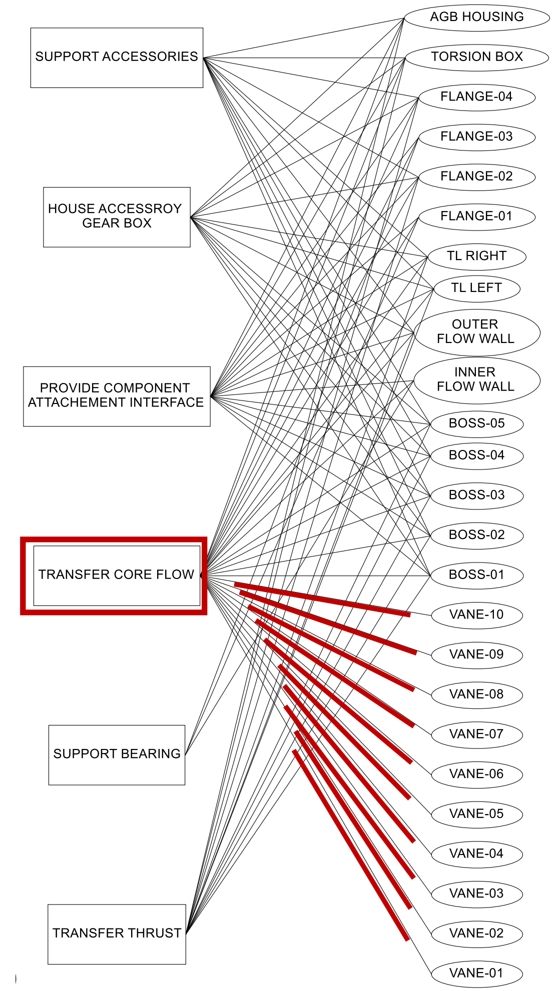


Sector Cast





Separate Cast



Split-type affects functional and function-section relational importance

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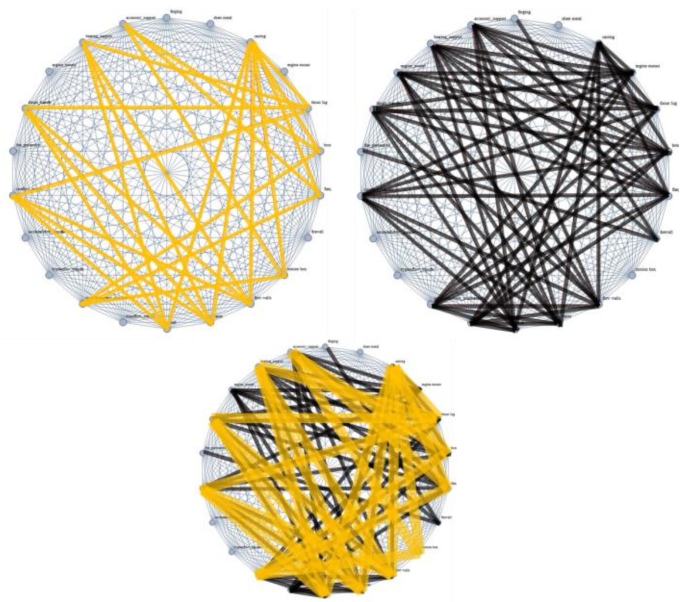
RQ4

How can a quantitative metric be created for the architecture so that comparison among products of the same class is made easier?

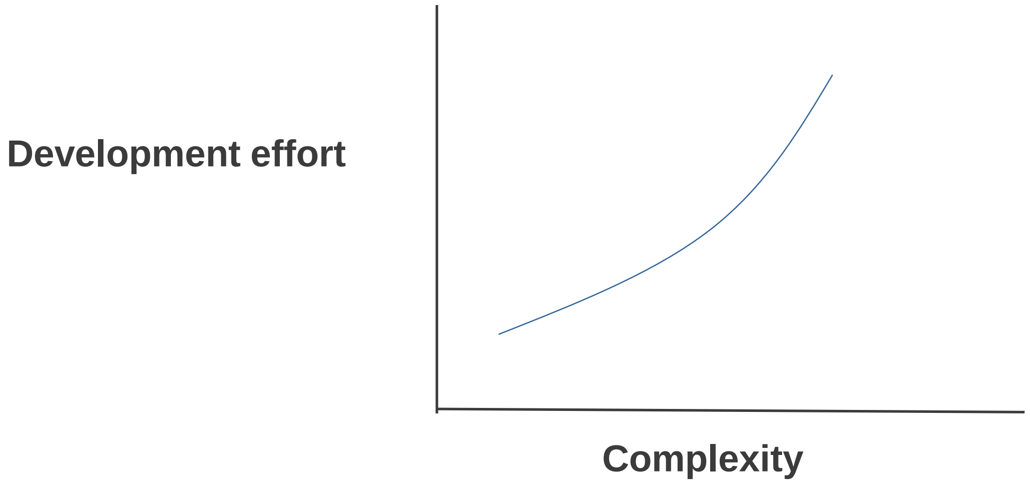
Complexity



- Complexity as “connectedness”
  - Physical domain
  - Relatively easy to calculate
- Complexity as “lack of information”
  - Functional domain

Complexity Metrics

- Generally for multi-component systems & multi-part products
  - Not readily applicable for functionally integrated products
- Often correlated with development effort
  - Development effort, $E = KC^b$; $b>1$*

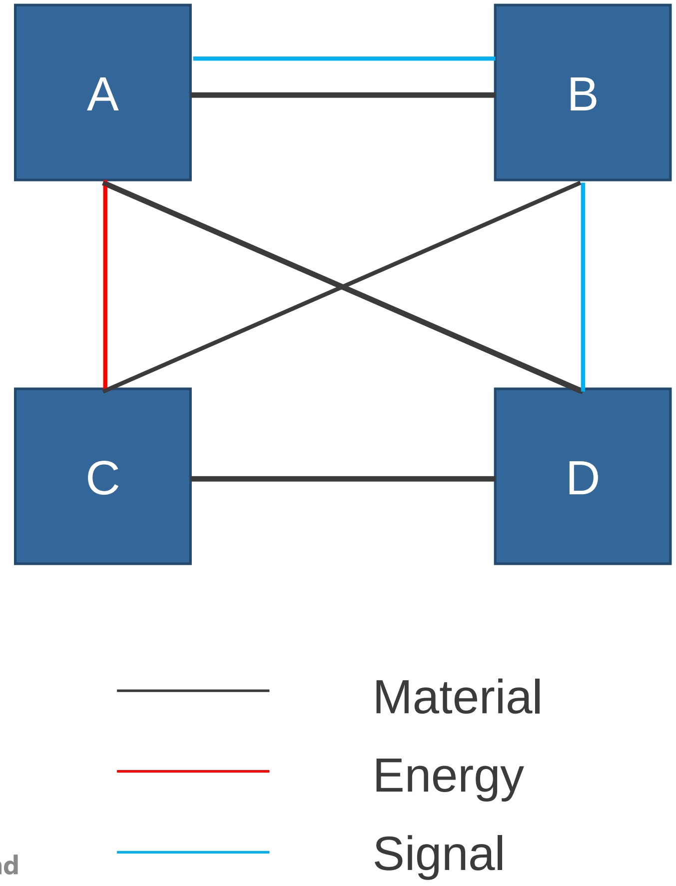


Metric for Aero-engine structures?

* SINHA, K. & DE WECK, O. L. 2016. Empirical Validation of Structural Complexity Metric and Complexity Management for Engineering Systems. *Systems Engineering, 19, 193-206.*

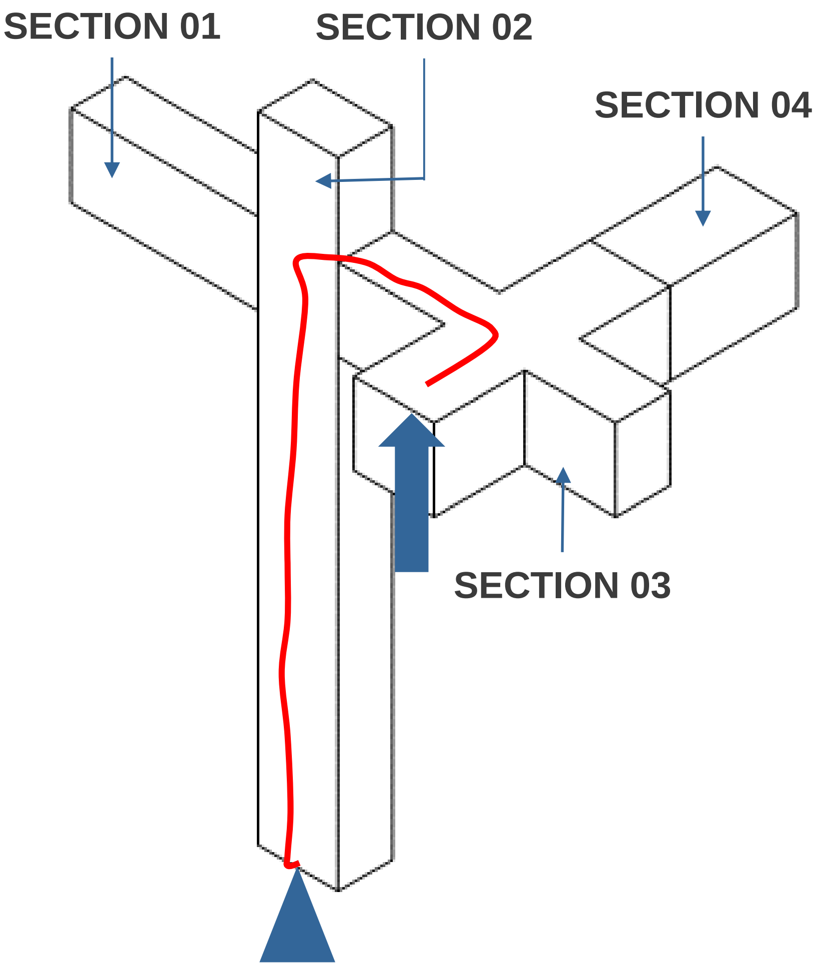
A Metric for Complexity

- Overall system complexity = sum of three complexities§
- C1
  - Individual sub-system complexities
- C2
  - Sub-system interaction complexity (flows)
- C3
  - Overall sub-system connectivity
- C = C1+C2C3



§ SINHA, K. & DE WECK, O. L. 2016. Empirical Validation of Structural Complexity Metric and Complexity Management for Engineering Systems. *Systems Engineering, 19, 193-206.*

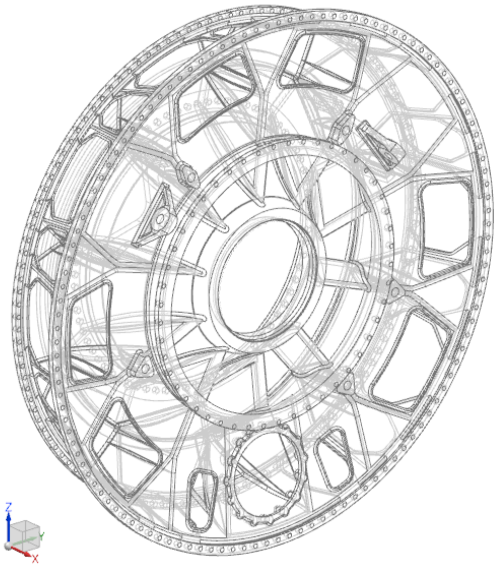
Example with One Type of Flow: Load



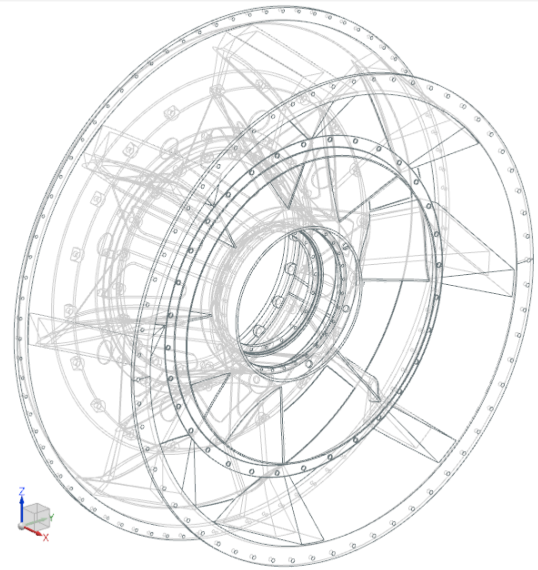
- The load path
  - Load ‘travels’ through 03 and 02
  - Important consideration for structures design
- Different load paths for:
  - Different loading scenarios
  - Different geometries
- Determined using structural optimization

- Use sections for components
- Use load path as sectional interaction

Complexity for Engine Structures

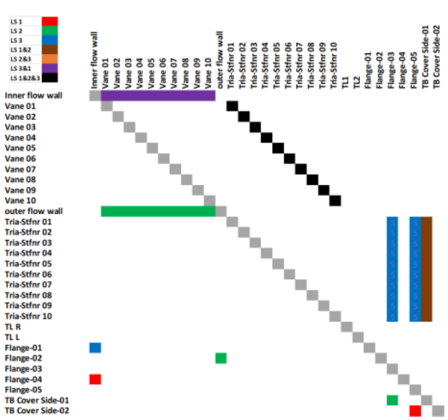


C = 465

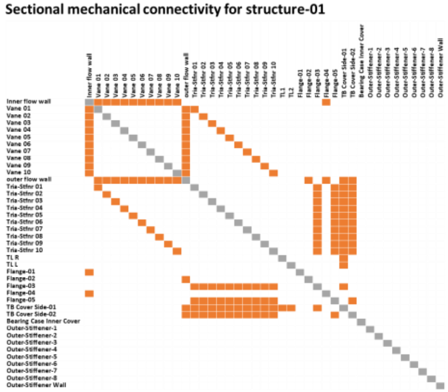


C = 582

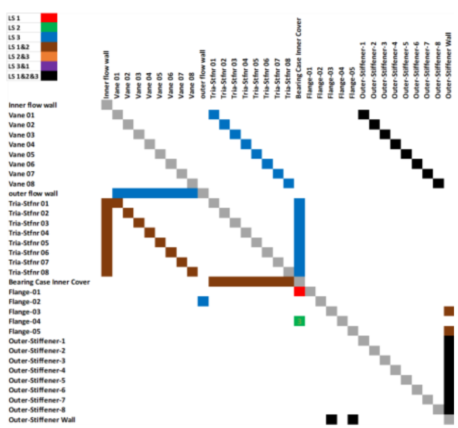
Load path sectic



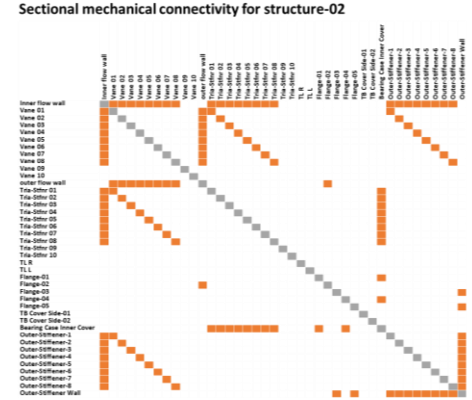
Sectional mechanical connectivity for structure-01



Load path sectional adjacency for structure-02



Sectional mechanical connectivity for structure-02



25% difference in complexity; 48% more development effort

Research Questions Revisited

A

How does the product behave in the system?

B

How does the product adapt to the system?

RQ 1

What are the effects of engine structures on the performance of the engine?

RQ 2

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Summary

https://research.chalmers.se/person/visakha

- Aero-engine structures design
- Functionally integrated products
- Architecture for understanding and evaluation
- Complexity for comparison and effort estimation

On the Design of Functionally Integrated

Aero-engine Structures:

Modeling and Evaluation Methods for Architecture and Complexity

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Conclusion

- Realise previously unseen functional interactions
- Predict development effort for future designs

With the aid of the developed methods, development engineers can “dissect” their products and compare alternative architectures.

Further Work

- System-component interaction in more detail
  - Include more variables (such as stiffness)
- Expanding the complexity metric
  - Implementation in in-house design evaluation system
  - Include flow path and manufacturing split options
- Represent human involvement also in architecture
- Further developing load path visualization

Thank You!