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TECHNOLOGY INSERTION IN TURBOFAN ENGINE AND ASSESSMENT OF ARCHITECTURAL COMPLEXITY

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ABSTRACT

The design and development of a gas turbine engine is a highly integrated process, and requires the integration of efforts of large numbers of individuals from many design specialties. In the case that there are significant architecture changes due to technology insertion, customer requirements or component configuration for performance, integration of design efforts become more challenging. . The analysis presented here compares a traditional two spool turbofan engine with a two spool engine incorporating a gear reduction between the fan and the driving spool. This is known as "Geared Turbofan" (GTF) engine architecture. The analysis presented here shows that the change in engine architecture represents a move to a more distributed and less modular architecture. The DSM shows a 20% increase in density of connectivity between components and 40% increase in terms of structural complexity. The impact of these changes suggests that the more distributed architecture of the new-generation geared turbofan architecture likely will require more system integration effort than the traditional turbofan architecture.

Keywords: Design Structure Matrix (DSM), structural complexity, technology insertion, architectural comparison, organizational impact

1. INTRODUCTION

The two architectures compared in this work are two potential embodiments of large commercial gas turbine aircraft engines. The first is a typical two spool turbofan engine, and the second is a turbofan with a gear reduction system to reduce the fan speed. The comparison is of interest because of the potential benefits of the geared turbofan architecture in fuel burn and noise. The impact of this architecture on the organization, design and development process would then stem from the differences in the relative complexity of the architecture, as well as the organizational and process boundaries overlaid on the architecture.

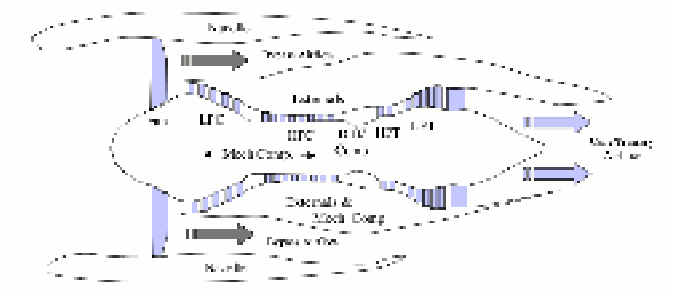

Figure 1. Typical commercial gas turbine engine with major functional modules identified

Both are axial flow, high bypass ratio gas turbine engines. Table 1 shows a comparison of key specification parameters of both engines. Both engine architectures fundamentally provide similar primary function like thrust generation to the customer (though magnitude of maximum generated thrust are different in these two cases), but arrive at that function through different architectural arrangement.

Parameter	Old turbofan	New turbofan
Fan tip diameter:	112 in	73 in
Takeoff thrust:	74,000 - 90,000 lb	21,000-23,3000 lb
Bypass ratio:	5.8 - 6.4	12
Overall pressure ratio:	34.2 - 42.8	44.5

Table 1. Comparison of traditional turbofan and new turbofan

2. DSM DEVELOPMENT

The DSM was constructed for the two engines to allow comparison of the two architectures. This then provides the following benefits [13]:

- Measurable framework for comparison of architecture between the GTF and traditional turbofan platforms.
- Provide a platform to perform modularity analysis using the different algorithms
- Provide a platform to overlay the architecture, modules and components on the organizational structure, to determine how the architecture may impact the design and development process through organizational interactions.

Development of a DSM for a complex system requires that a level of abstraction be made. The level of abstraction must align with the analysis being performed [4]. The subject of this work is to examine the changes brought to the relationships between the organization and the architecture - and how the differences in the architecture of a traditional turbofan and a geared turbofan may influence the design, validation and field experience of the engine itself. The DSM is then created with an abstracted view of the components to provide the ability to assess the system complexity as well as the organizational connectivity between teams responsible for the design and development of the engine components. Components for the DSM were selected based on their need for inclusion as a result of the functional decomposition of the engine. While the engines studied are designed for significantly different airframe applications, the degree of abstraction of function allows comparison because of the similarity of the product application. This need is met through addressing both the “scope” and “granularity” of the matrix [4]. A balance is needed in having sufficient detail to perform the required analysis, without making the DSM generation process so cumbersome as to be a design and development process in itself. This DSM generation method is reflected in the system level decomposition, which can be seen to clearly apply equally to both platforms. Components represented in the DSM were selected based on this functional representation of the system. Experience was that a matrix with approximately 75 to 85 components was sufficient to represent complexity of a large scale printing system [4, 12]. The DSM generation proceeded without limitation to the number of components, but was found to be within the guidelines proposed. In the DSM constructed, the multiple airfoils per stage, and multiple stages per module were simplified to one. Repeated features in the architecture are not believed to add architectural complexity, and are not included. For example, the bearing compartments were aggregated to provide the rotor supporting function and connect the rotors (rotating) to the static (cases), as well as provide all of the internal supporting functions (lubrication, sealing, and power extraction).

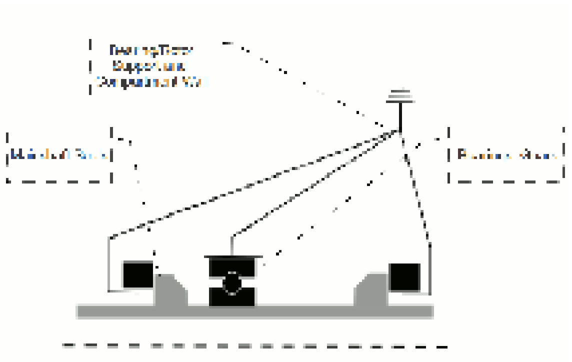

Figure 2. Aggregation of a typical bearing compartment

With the components that define the system architecture identified, the connectivity of those components to map the value delivery internal to the machine was populated through the matrix using connectivity mapping and encoding scheme. The challenge in creating an effective DSM was to prune the component list to only what was functionally required to represent the architecture of the engines for comparison purposes [4, 12].

3. DSM Encoding

Many DSM's used to date are binary, and represent connectivity of the components or process simply by indicating if a connection exists or not. In order to develop a deeper understanding of the gas turbine engine, a more detailed approach is taken using a "quad" connection structure is utilized (Suh et al, 2008). This provides the ability to analyze the network from different views, and to segregate relationships based on connection type – which may have different impacts on the design and development of the machine, and also will likely be represented by different experts in the design process – which will aide in the investigation of the architectural impact on the social layer interactions. In addition, the different types of flows (core flow, bypass flow, fuel flow, oil flow and secondary flow) are critical to understanding the energy flow through a gas turbine engine, and this refinement is proposed in this thesis as a method of adding further detail to the DSM. To capture the benefit of having this information stored in the DSM, a scheme was developed to "encode" all of the information into a single integer based on a 2^n - 1encoding scheme. The quad based DSM structure (mechanical connection, flow connection, information, and energy) could then be generated in a spreadsheet such as Excel, and then "encoded" into a square adjacency matrix of connections for network analysis and visualization. Tools to facilitate the encoding and decoding of the matrices were developed in Perl. In order to represent the different types of flows in the DSM, each quantity to be represented was given an integer number of the scheme 2^n - 1. Each connection between components has one or more of the basic encoding types, with additional detail added by using the detail encoding in addition to the basic encoding. The following scheme is used:

N	Flag	Flow Type	Description
0	0	None	No connection
1	1	Mechanical	Physical coupling between components. This is by nature symmetric.
2	3	Fluid Flow	Flows of any fluid between two components
3	7	Information	Information transfer between components. Generally assumed to be electronic measurement for sensors, etc.
4	15	Energy	Energy transfer of any energy type.

Table 2. Basic encodings for the gas turbine engine DSM

N	Flag	Flow Type	Description
5	31	Gaspath flow	Flow through the engine "core" which passes through the compressors and turbines
6	63	Bypass flow	Flow through the fan only, bypassing the engine core

7	127	Secondary Flow	Air flow taken off of the gas path or bypass flows and used for component cooling or pressurization
8	255	Fuel flow	Fuel flows through the fuel system. Ends at the fuel nozzles, exhaust products are considered gas path flow.
9	511	Oil flow	Oil flows through the lubrication system.
10	1023	Torque	Transfer of torque between components
11	2047	Electrical Energy	Transfer of electrical energy between components
12	4095	Chemical Energy	Transfer of chemical potential energy between components. Aides in visualization of energy transfer pathways and conversion of chemical potential to thermal energy.
13	8191	Thermodynamic Energy	Transfer of thermodynamic energy between components, including both pressure and temperature, generally considered enthalpy. Used for gaspath flow energy transfer.
14	16383	Hydraulic Energy	Transfer of pressure energy between components. While this could be considered part of thermodynamic energy, this is used for hydraulically actuated systems that operate on pressure differentials.

Table 3. Detail level encoding for the gas turbine engine DSM

The DSM's were generated for both the engines with similar levels of aggregation. The traditional turbofan DSM has 69 components, and the new generation geared turbofan DSM has 73 components. The size of the two matrices is close enough for comparison purposes, and since they were developed with the same guidelines for aggregation this is believed to represent the architecture properly for this purpose.

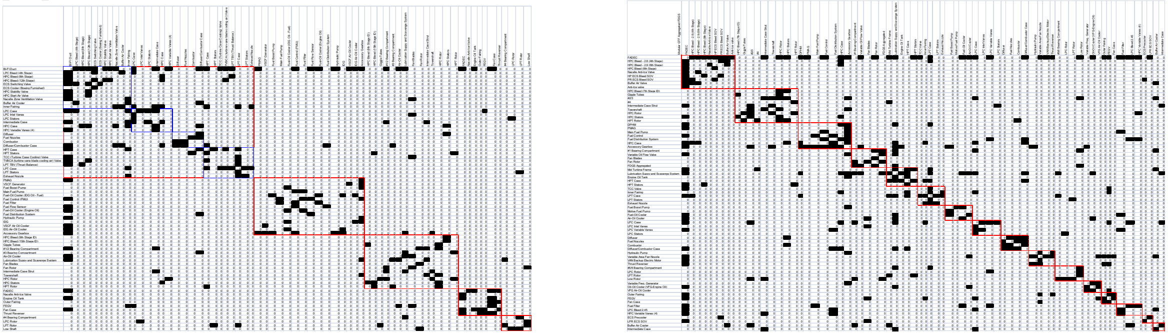

Figure 3. DSM of old and new architectures

4. Architecture Comparison

The two architectures represented show some fundamental differences in density and connectivity. This is likely attributed to the higher integration of the geared turbofan, a smaller and modern engine. This increase in structural complexity can be seen visually in a comparison of the two DSM's, and is also demonstrable through computed metrics. The structural complexity and modularity metrics were computed along with connectivity details to demonstrate differences in their architectural characteristics. The structural complexity metric is defined below [12,15]:

$$\underset{\text{complexity}}{C(n,A)} = \underbrace{\sum_{i=1}^{n}\alpha_i}_{\text{components}} + \underbrace{\left[\sum_{i=1}^{n}\sum_{j=1}^{n}\beta_{ij}A_{ij}\right]}_{\text{interfaces}}\gamma\underbrace{E(A)}_{\substack{\text{architecture}\\ \text{graph energy}}}$$

where first term represents complexity of the individual components (containing the α's), the second term brings in an extra contribution of complexity due to the number of interactions and the way the components are arranged. This second term is the interesting one and it is the scaled product of the total number of interfaces and graph energy (e.g., sum of singular values of the aggregated DSM) [5–9]. This complexity metric was developed to represent the complexity of a system as the sum of the two terms for component complexity and the architectural impact respectively. The component complexities are assessed and reflect the internal complexity of the individual components in the DSM. These are determined by "expert" review. The modularity index (Q) used here is the one introduced by Girvan and Newmam [10, 14].

	Older Architecture	New Architecture	Change
Components	69	73	6%
Connection Density	5.73%	6.87%	20%
Connections (all)	269	361	34%
Mechanical	240	326	36%
Information	47	48	2%
Energy	58	60	3%
Flow	87	105	21%
Graph Energy, E(A)	104.4	123.3	18%
Modularity Index (Q)	0.43 (5 Modules)	0.35 (16 Modules)	-20%
Structural Complexity	548	767	40%

The DSM for the new architecture shows significantly more connectivity in all areas measured, with a 20% increase in connection density of the DSM. The individual connection types all increased in number, reflecting a more inter-connected architecture. The largest increase, 36%, is found for the mechanical connections. This higher level of interconnectivity would lead to the conclusion that the engine itself may have become slightly less "modular", and this is reflected in the decrease in the modularity (Q) index, and increase in the number of modules. The increase in graph energy E(A), indicates that the system is more distributed than the traditional turbofan architecture represented. The modularity analysis performed for both engine architectures using the total connectivity of the DSM showed that there are many potential modules. Some of the modules have relatively few components, because of their high relative internal connectivity strength. These modules are likely good candidates to be worked by a single organization or team, because of the tightly coupled dependencies. Some of the modules highlighted using this technique is similar to groupings used in the industry, such as the compressor module, combustor/diffuser module and secondary flow system. The detailed architectural analysis using network representation reveals that primary functionality generators (e.g., generating thrust) are significant contributors to component complexity while supporting systems (e.g., lubrication systems, accessory gearbox, robust control systems) are the primary contributors to architectural complexity and having significant impact on system integration efforts [3,14]. Most of the rotating components showed low sensitivity to the structural complexity. Supporting systems like the engine control system, lubrication system, and accessory gearbox are found to be more sensitive to structural complexity.

5. CONCLUSIONS AND FUTURE WORK

The analysis performed developed a DSM to represent the architecture of a traditional turbofan engine and compared that with the DSM of new-generation geared turbofan architecture. The analysis showed that there was a significant increase in connectivity across the components that comprise the function of the machine, and these components formed a more "distributed" architecture than the more traditional engine layout [3,12]. The increase in architectural complexity is enabling a significant increase in predicted engine performance metrics for noise and fuel consumption, and the architectural changes may represent a "disruptive" type change in the large commercial engine market [2,14]. With the linkage between the DSM (architecture) and functional groups made, the potential impact of the architecture on the organization and integration effort can be assessed. From the business impact perspective, using the analysis performed may provide some insight into the connections between architectural complexity and integration cost.

Future work would concentrate on the impact of physical architecture on the organizational interactions. Preliminary analysis showed that this resulted in an increase in functional group connectivity overall, and most importantly, resulted in significant novel connections between functional groups that did not require interfacing on the older architecture. This indicates a close interplay between the product architecture and organizational architecture of the product development team in a feedback sense. A significant novelty in the product architecture is likely to prompt an organizational change to make the product development process more efficient.

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Technology Insertion in Turbofan Engine and Assessment of Architectural Complexity

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Introduction

- Traditional turbofan engines have a fixed shaft connecting the fan with low pressure compressor and low pressure turbine.

- New generation geared turbofan engine includes a fan drive gear system that enables fan and low spool shaft to rotate at their individual optimal speeds. This leads to an ultra-high bypass ratio turbofan engine.

- This new architecture brings about very significant performance gain in terms of multiple engineering attributes. About 15% reduction in fuel burn (lower TSFC), significant reduction in noise level (by 50% - 75%) and also significantly reduced emission level. Development of new generation of turbine and compressor components.

- But this performance gains led to significant requirements on supporting systems like controls, lubrications, etc. and increased complexity. We investigate the impact due to insertion of new technology (e.g., gear system in this case) on product architecture and organization.

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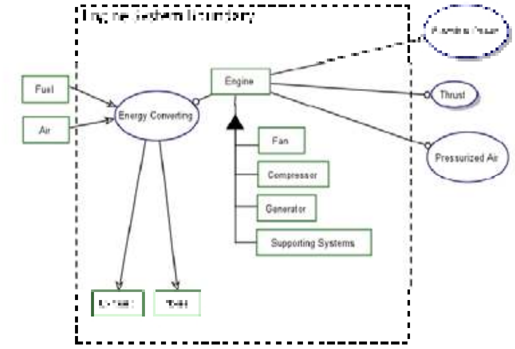
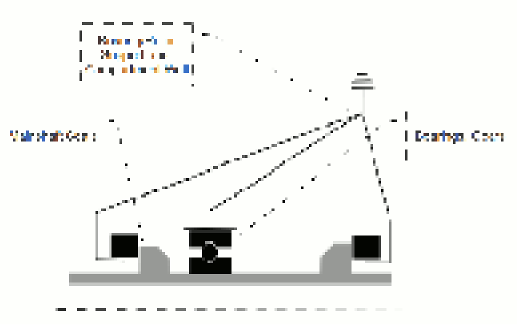
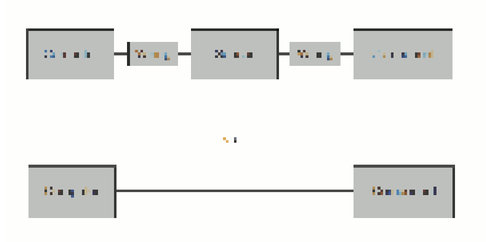
DSM Building Conventions



Three primary propulsion system delivered functions



Aggregation of a Typical Bearing Compartment



Example of Aggregation of Component Abstraction

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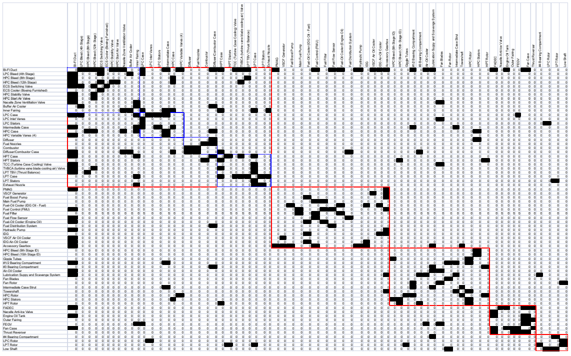
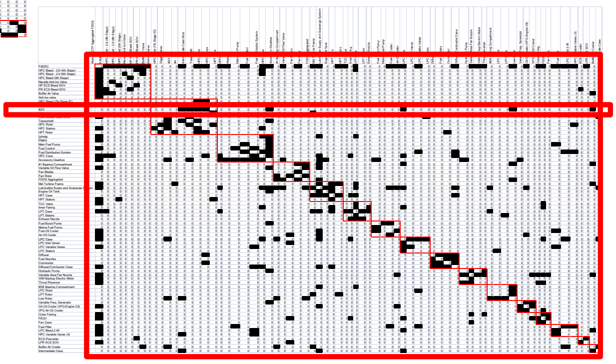
DSMs for Comparison



Old Architecture

- Constructed from cross sections, schematics, expert interviews
- Similar level of decomposition in both for comparison purposes
- Limited Component aggregation based on design expertise required

New Architecture



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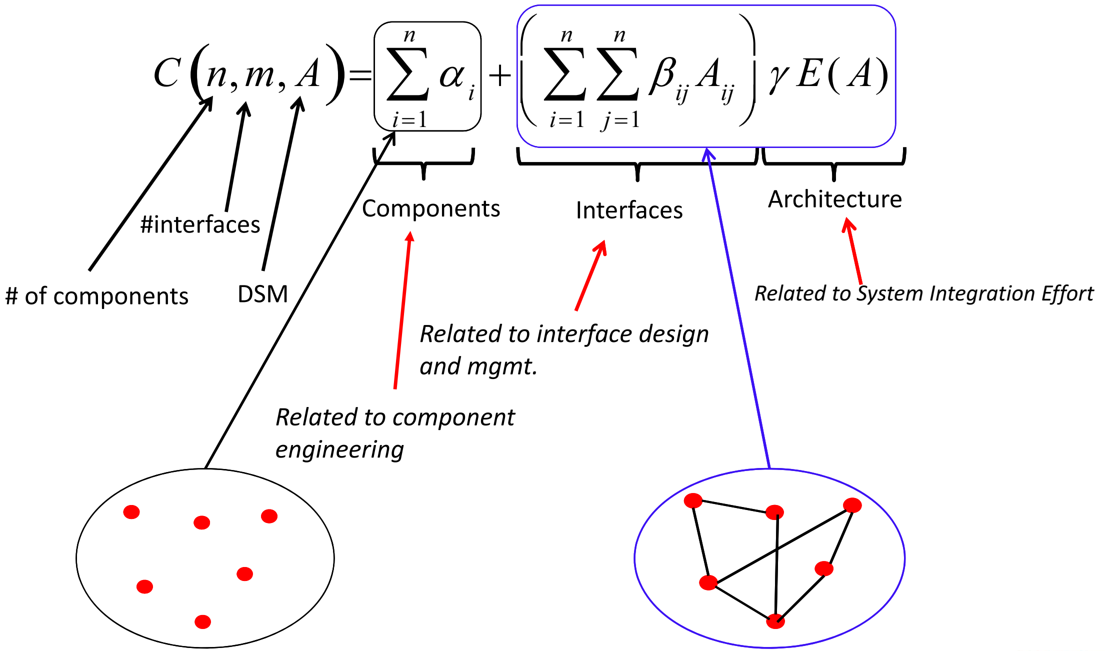
Structural Complexity Equation



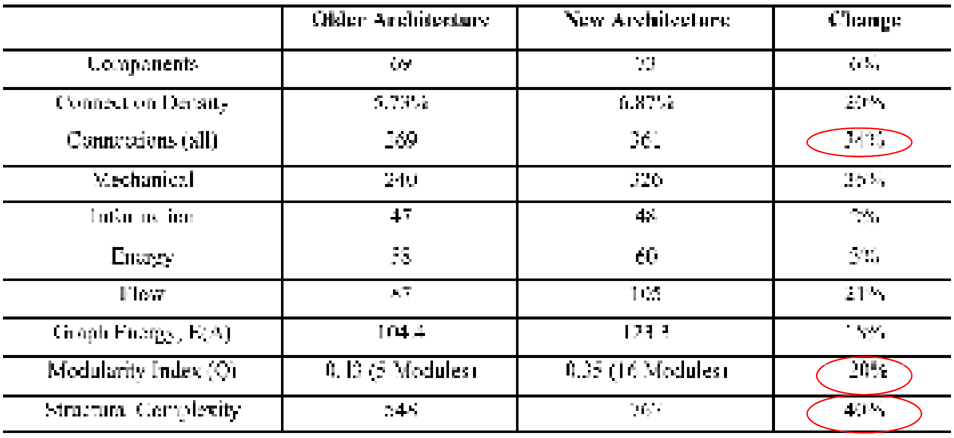
$$C(n,m,A) = \underbrace{\boxed{\sum_{i=1}^{n}\alpha_i}}_{\text{Components}} + \boxed{\underbrace{\left(\sum_{i=1}^{n}\sum_{j=1}^{n}\beta_{ij}A_{ij}\right)}_{\text{Interfaces}}\underbrace{\gamma E(A)}_{\text{Architecture}}}$$

Related to component engineering

Related to interface design and mgmt.

Related to System Integration Effort

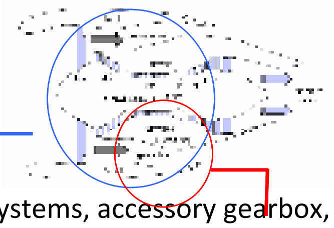
Architectural Comparison



	Older Architecture	New Architecture	Change
Components	69	73	6%
Connection Density Connections (all)	5.73% 269	6.87% 361	20% 34%
Mechanical	240	320	33%
Information Energy	47 55	48 60	2% 9%
Flow	87	105	21%
Graph Energy, E(A)	104.4	123.3	18%
Modularity Index (Q)	0.13 (5 Modules)	0.35 (16 Modules)	20%
Structural Complexity	548	767	40%

Component Sensitivity to Complexity

- Compared complexity of different architectures, identified areas that drive complexity
  - Primary functionality generators (e.g., generating thrust) are significant contributors to component complexity
    => *component engineering*



  - Supporting systems (e.g., lubrication systems, accessory gearbox, robust control systems) are the primary contributors to architectural complexity
    => *system integration efforts*
- Compared sensitivity of each component to complexity measure.
  - Most of the rotating components, had low sensitivity to the architectural complexity.
  - Supporting systems like FADEC, lubrication system, accessory gearbox are more sensitive to architectural complexity.

Impact on Verification and Validation

Component	HP Turbine Rotor	Buffer Air Cooler
Component Complexity	High	Low
Architectural Complexity	Low	High
Total Connections (aggregated)	5	8
Participation factor	0 (all connections within module)	0.67 (highly distributed, across modules)
Architectural Impact	Locally Connected	Highly Distributed
Validation Requirements	Module Level	System Level

Low complexity, highly distributed components drives system level (expensive) testing requirements for the engine family.

Organizational Impact of GTF Architecture

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Interplay of Product Architecture and Organization

- Anticipation of where gaps may exist due to architectural change
  - Connections where legacy turbofan architecture may not have connectivity or processes defined based on prior architectures
- Areas of strategic integration importance where close control is critical.
- Organizational alignment to minimize *boundary crossing* in the design and development process

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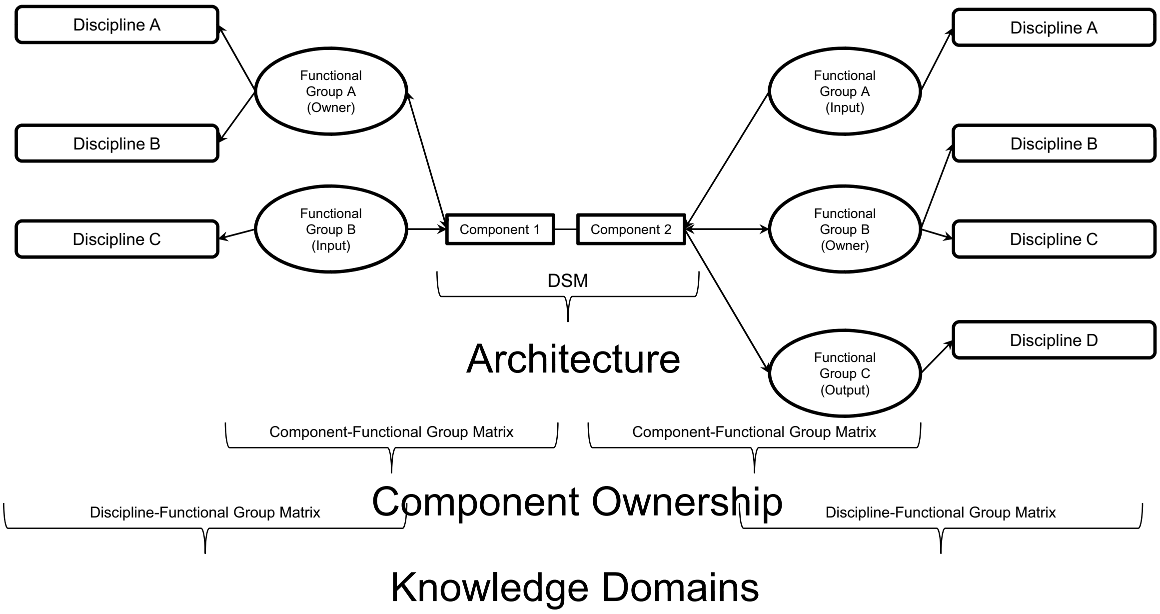
Linkage between Architecture, People and Methods



DMM: Maps DSM to Organization

Component-Functional Group Matrix

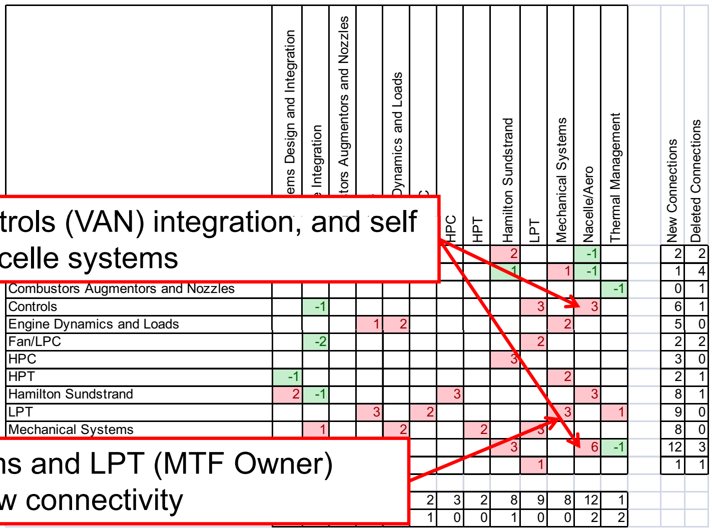
Linkage of Component Design Owners with Components for the PW4098	Controls	Hamilton Sundstrand	Air Systems Design and Integration	Support Equipment Organization	Externals	Thermal Management	Mechanical Systems	Engine Dynamics and Loads	Nacelle/Aero	Fan/LPC	Combustors, Augmentors and Nozzles	Engine Center	HPC	HPT	LPT
Fuel Flow Sensor		■													
Hydraulic Pump		■													
IDG		■													
LPC Bleed (4th Stage)			■												
HPC Bleed (8th Stage)			■												
HPC Bleed (12th Stage)			■												
HPC Bleed (11th Stage ID)			■												
Giggle Tubes			■												
Nacelle Anti-Ice Valve			■												
HPC Stability Valve													■		
HPC Start Air Valve													■		
Nacelle Zone Ventillation Valve			■												
#3 Buffer Air Cooler						■									
VSCF Air Oil Cooler						■									
Fuel-Oil Cooler						■									
Air-Oil Cooler						■									
Fuel-Oil Cooler (IDG Oil - Fuel)						■									
IDG Air-Oil Cooler						■									
Anti-Ice valve			■												
#1/2 Bearing Compartment							■								
#3 Bearing Compartment							■								

Indicates Component Ownership

- Linkage between components and “functional groups”

Significant Number of New Connections between Functional Groups

- A significant number of new connections between functional groups has been driven by new co the archite
- New connections between functional groups may not have processes in place or experie effectiv of need



	ems Design and Integration	e Integration	tors Augmentors and Nozzles		Dynamics and Loads	C	HPC	HPT	Hamilton Sundstrand	LPT	Mechanical Systems	Nacelle/Aero	Thermal Management		New Connections	Deleted Connections
									2			-1			2	2
									-1		1	-1			1	4
Combustors Augmentors and Nozzles													-1		0	1
Controls		-1								3		3			6	1
Engine Dynamics and Loads				1	2						2				5	0
Fan/LPC		-2								2					2	2
HPC									3						3	0
HPT	-1										2				2	1
Hamilton Sundstrand	2	-1					3					3			8	1
LPT				3		2					3		1		9	0
Mechanical Systems		1			2			2		3					8	0
									3			6	-1		12	3
										1					1	1
						2	3	2	8	9	8	12	1			
						1	0	0	1	0	0	2	2			

Nacelle and Controls (VAN) integration, and self integration of Nacelle systems

Mechanical Systems and LPT (MTF Owner) have significant new connectivity

This information quantifies the impact of engine novelty on organizational alignment

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Significant Increase in Connectivity between Technical Disciplines

	Aero-Thermo Fluids	Controls and Diagnostics	Design	Structures	Systems Engineering
Aero-Thermo Fluids	68	12	11	0	-2
Controls and Diagnostics	11	-12	2	0	-2
Design	11	2	12	2	1
Structures	-1	1	2	2	0
Systems Engineering	-1	-2	1	0	0

Aggregate Connectivity Changes

Highlights Mechanical Design Interactions increasing.

	Aero-Thermo Fluids	Controls and Diagnostics	Design	Structures	Systems Engineering
Aero-Thermo Fluids					
Controls and Diagnostics					-2
Design				2	1
Structures		1	2	2	
Systems Engineering		-2	1		

New or Deleted Connections

- Some new connectivity between disciplines, primarily in the structures area

Difference between Technical Discipline connectivity matrix for new and old architectures

This information helps identify needs for new or improved engineering models/tools

Summary

- Analysis and Comparison of Engine Architectures
  - There is 34% increase in number of connections in new architecture.
  - About 40% increase in structural complexity of the architecture. This is expected to result in much higher system integration efforts.
  - Supporting systems (e.g., lubrication systems, accessory gearbox, control systems) contribute primarily to architectural complexity while primary thrust generators(e.g., fan, turbine components) contribute primarily to component complexity.
  - Non-commonality of simple components with highly distributed connectivity across engine variants may lead to much higher V&V expenditure.

- Organizational Impact of GTF Architecture
  - DMM shows interplay between physical components, their organizational ownership and technical disciplines.
  - Significant number of new connections between functional groups.
  - Significant Increase in connectivity between technical disciplines but relatively small increase in entirely new connectivity between disciplines that had no connectivity in prior engine architecture.