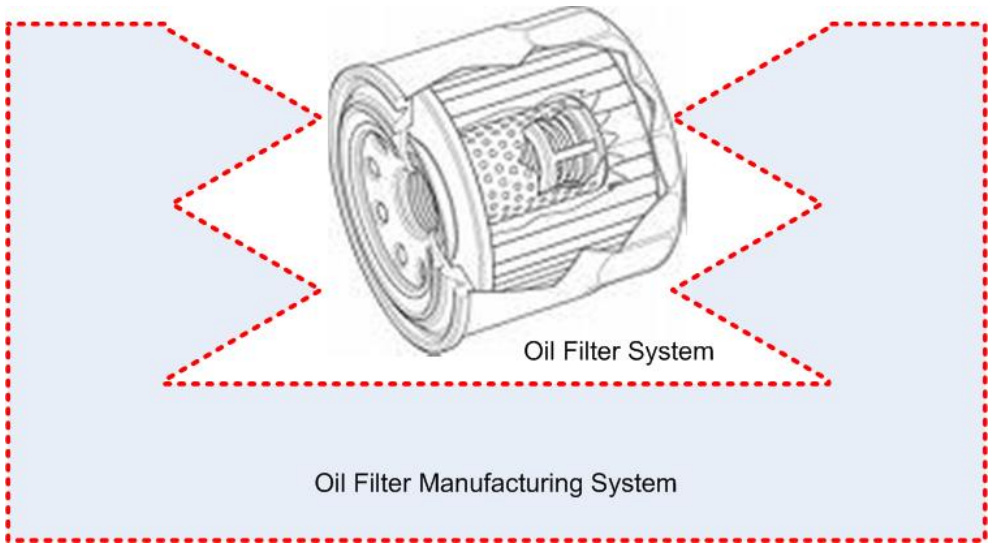
Samples from a simple illustrative example

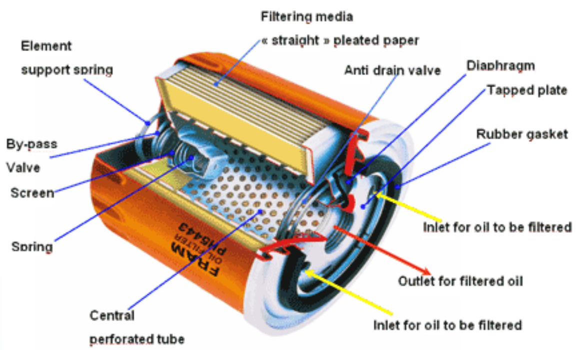


- Product: Oil Filter
- Manufacturing System: Oil Filter Mfg System

Physical Architecture Models describes the physical portion of the technology, to which Functional Roles will later be allocated and optimized . . .

Product Physical Architecture

Architecture 1: Laminated and Accordion Pleated Filtration Media, Flow Orthogonal to Plane of Media, Additive Impregnated

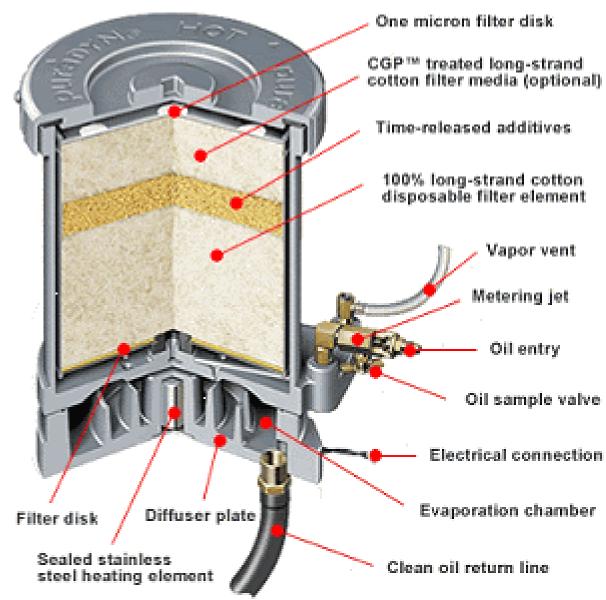


Synthetic
Filter Media

Paper
Filter Media

Stainless Steel
Filter Media

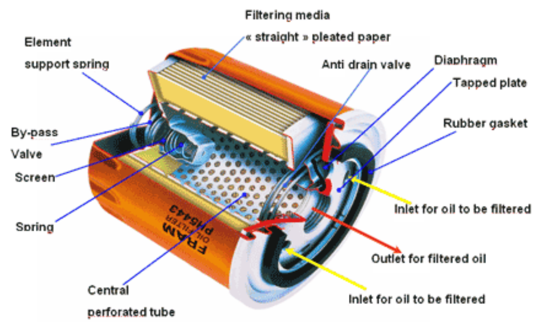
Architecture 2: Wound Filtration Fiber, Flow Orthogonal to Plane of Windings, Additive Impregnated



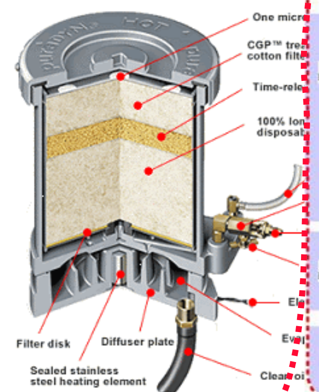
Physical Architecture describes the subject system's major physical components, their organization, and primary physical attributes.

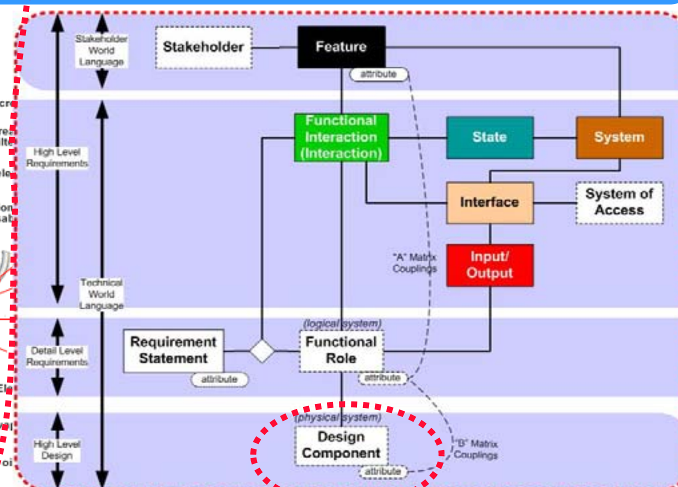
Product Physical Architecture

Architecture 1:



Architecture 2:



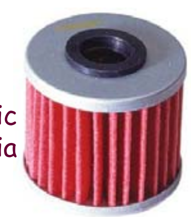


Different architectures

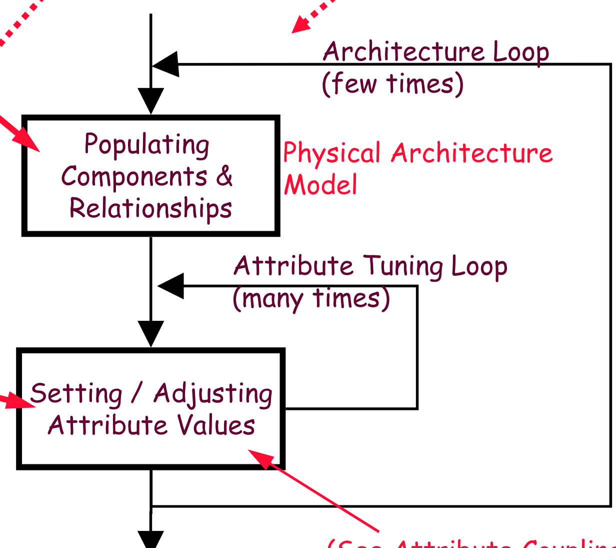
Different attribute values within same architecture

Paper Filter Media

Synthetic Filter Media



Stainless Steel Filter Media



(See Attribute Coupling Model)

Directly addressing a key SE challenge: How do we discover all the Requirements, including Manufacturing as well as others?

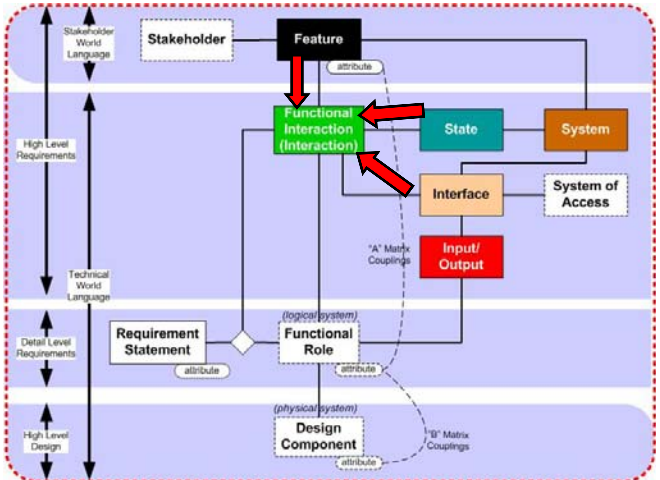
The three MBSE roads to finding all Requirements

MBSE provides a powerful paradigm for discovering all the Interactions, and therefore all the system Functional and Non-Functional Requirements:

1. Domain Model: Find all the external Actors that interact with the system.
2. State Model: Find all the States (situations, modes, phases, use cases) that the system will encounter.
3. Feature Model: Find all the Features valued by Stakeholders.

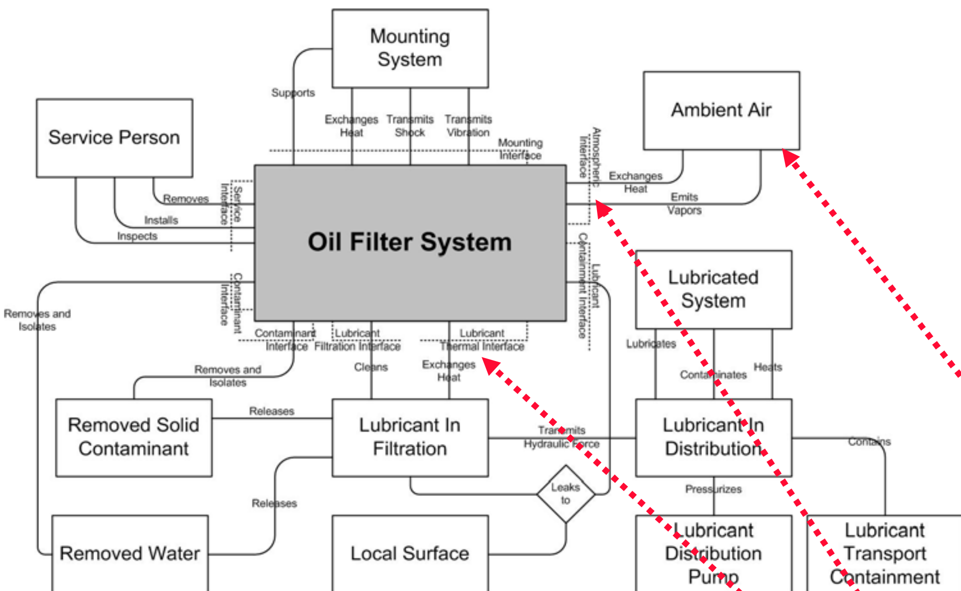
Benefit: These three (redundant) paths provide a higher-than-usual assurance of finding and validating all the Interactions and Requirements.

This is illustrated by the following example Model extracts . . . .

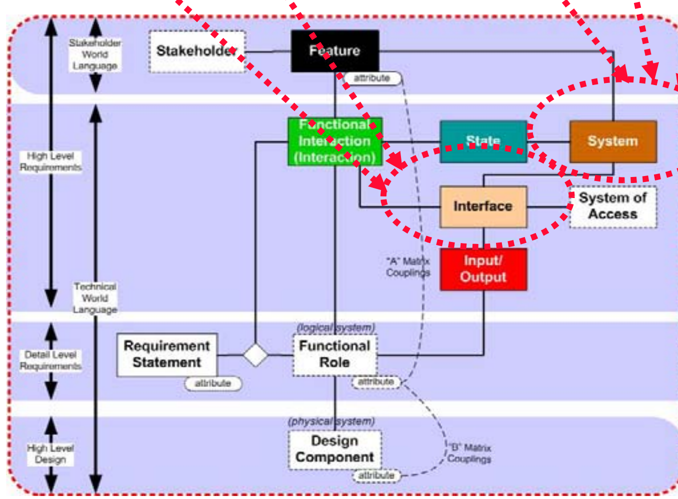


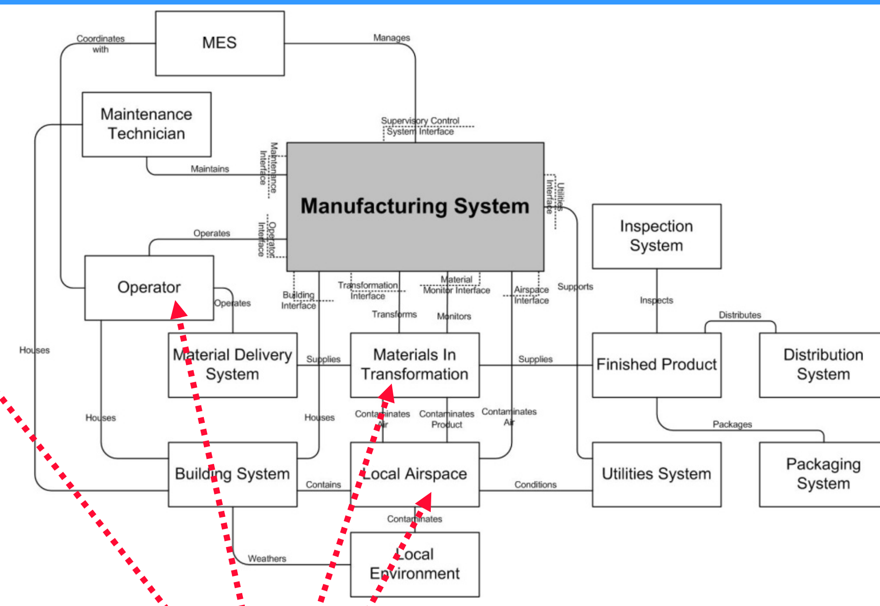
Domain Models directly help by discovering and capturing all the external systems physically interacting with the Subject System—these are the <u>source of all Functional Requirements</u>.

Domain Models



Product Application Domain Model



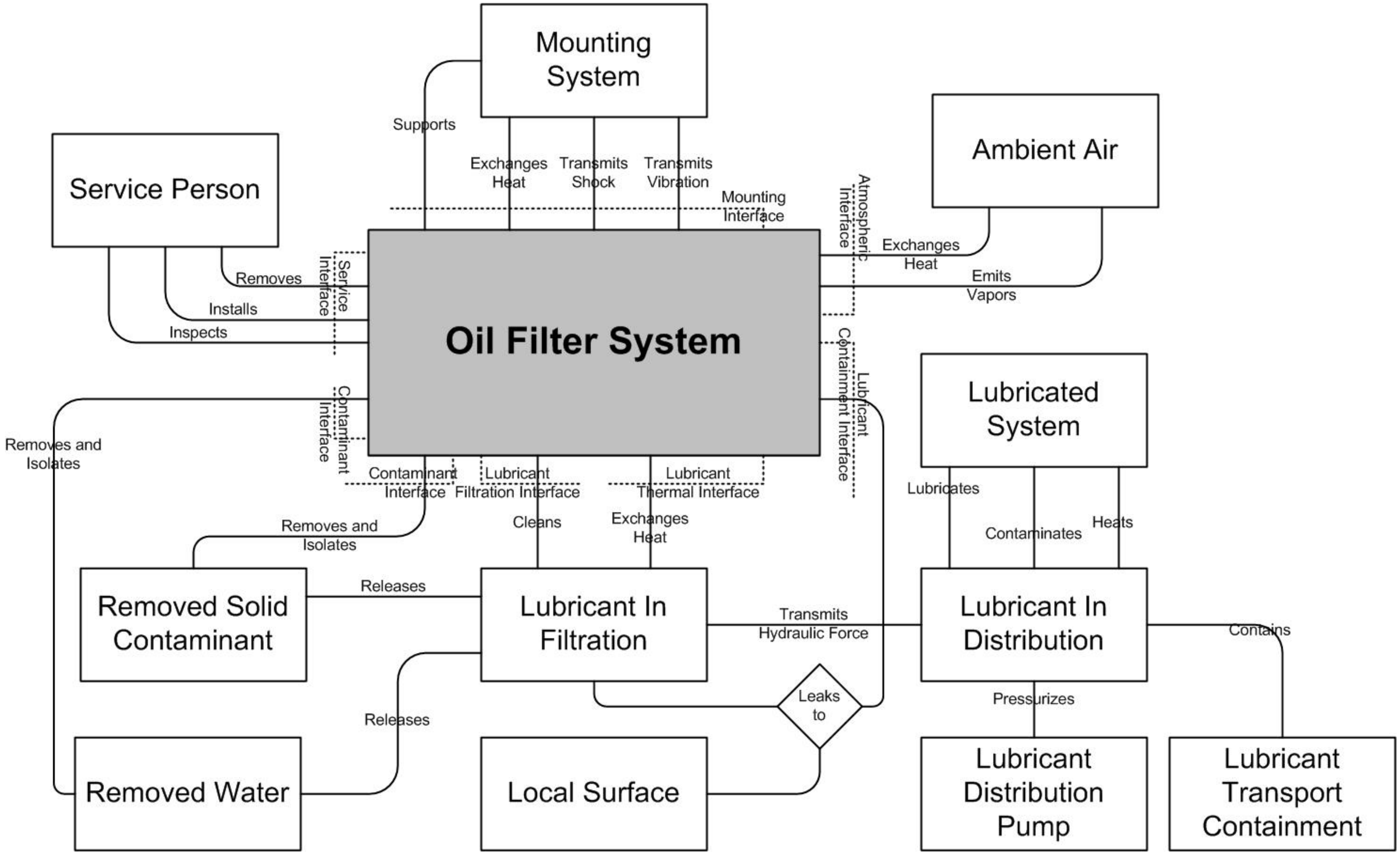


Manufacturing Domain Model

ICTT System Sciences

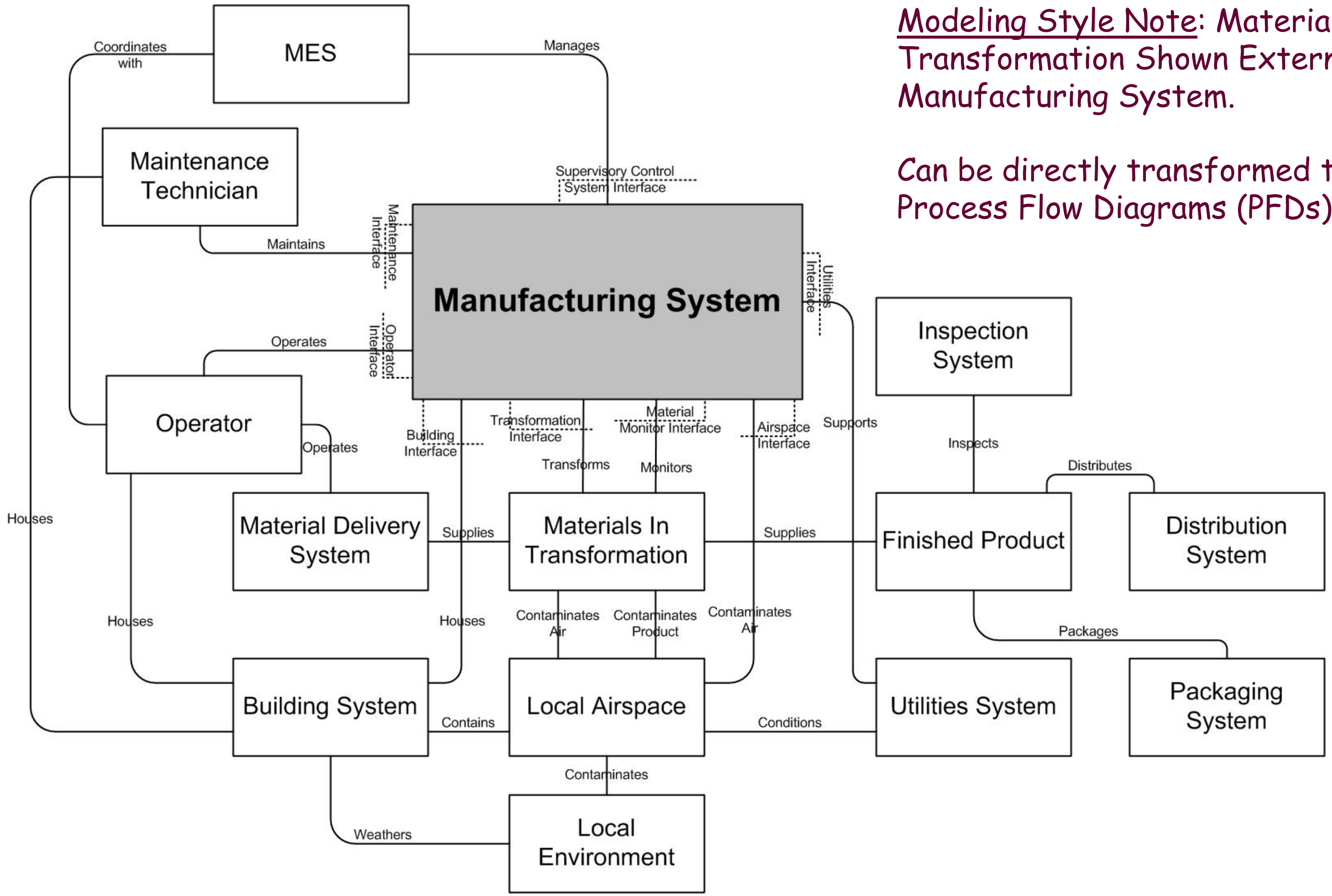
Domain Models show the external systems that interact with a Subject System over its domain life cycle. This defines the System Boundary, External Interfaces, Domain Relationships.

Product Application Domain Model



<u>Domain Models</u> show the external systems that interact with a Subject System over its domain life cycle. This defines the System Boundary, External Interfaces, Domain Relationships.

Manufacturing Domain Model



<u>Modeling Style Note</u>: Material In Transformation Shown External to Subject Manufacturing System.

Can be directly transformed to/from Process Flow Diagrams (PFDs).

Stakeholder Feature Models address a key SE challenge by making explicit the ultimate stakeholder outcomes against which <u>all decisions, trade-offs, optimizations, and outcomes</u> will be <u>scored and selected</u>. This covers <u>all</u> Stakeholders, not just Customers (e.g., Shareholders, Community, etc.)

Product Stakeholder Features, Feature Attributes

Microsoft Excel - Oil Filter Pattern V1.1.1.xls

I12 — The feature of providing services with a specified level of reliability over the normal operating life of a system.

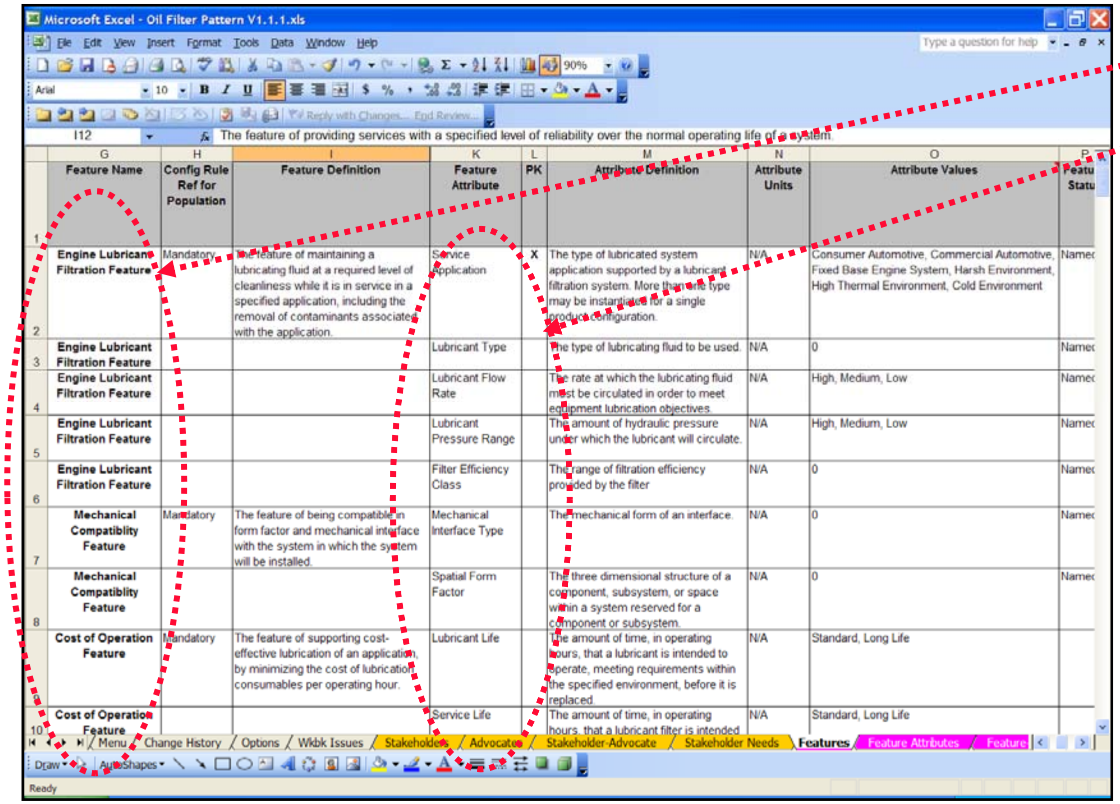
	G	H	I	K	L	M	N	O	P
1	**Feature Name**	**Config Rule Ref for Population**	**Feature Definition**	**Feature Attribute**	**PK**	**Attribute Definition**	**Attribute Units**	**Attribute Values**	**Featu Statu**
2	**Engine Lubricant Filtration Feature**	Mandatory	The feature of maintaining a lubricating fluid at a required level of cleanliness while it is in service in a specified application, including the removal of contaminants associated with the application.	Service Application	X	The type of lubricated system application supported by a lubricant filtration system. More than one type may be instantiated for a single product configuration.	N/A	Consumer Automotive, Commercial Automotive, Fixed Base Engine System, Harsh Environment, High Thermal Environment, Cold Environment	Namec
3	**Engine Lubricant Filtration Feature**			Lubricant Type		The type of lubricating fluid to be used.	N/A	0	Namec
4	**Engine Lubricant Filtration Feature**			Lubricant Flow Rate		The rate at which the lubricating fluid must be circulated in order to meet equipment lubrication objectives.	N/A	High, Medium, Low	Namec
5	**Engine Lubricant Filtration Feature**			Lubricant Pressure Range		The amount of hydraulic pressure under which the lubricant will circulate.	N/A	High, Medium, Low	Namec
6	**Engine Lubricant Filtration Feature**			Filter Efficiency Class		The range of filtration efficiency provided by the filter	N/A	0	Namec
7	**Mechanical Compatiblity Feature**	Mandatory	The feature of being compatible in form factor and mechanical interface with the system in which the system will be installed.	Mechanical Interface Type		The mechanical form of an interface.	N/A	0	Namec
8	**Mechanical Compatiblity Feature**			Spatial Form Factor		The three dimensional structure of a component, subsystem, or space within a system reserved for a component or subsystem.	N/A	0	Namec
9	**Cost of Operation Feature**	Mandatory	The feature of supporting cost-effective lubrication of an application, by minimizing the cost of lubrication consumables per operating hour.	Lubricant Life		The amount of time, in operating hours, that a lubricant is intended to operate, meeting requirements within the specified environment, before it is replaced.	N/A	Standard, Long Life	
10	**Cost of Operation Feature**			Service Life		The amount of time, in operating hours, that a lubricant filter is intended	N/A	Standard, Long Life	

Menu / Change History / Options / Wkbk Issues / Stakeholders / Advocates / Stakeholder-Advocate / Stakeholder Needs / **Features** / Feature Attributes / Feature-

Ready

Features are collections of Functional Interactions (behaviors) having value to Stakeholders; their Attributes quantify that value impact. Features are in language of Stakeholders.

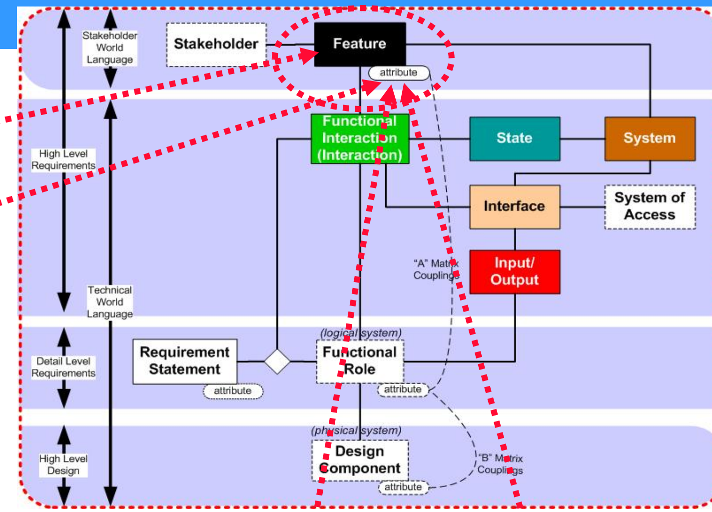
Product Stakeholder Features, Feature Attributes



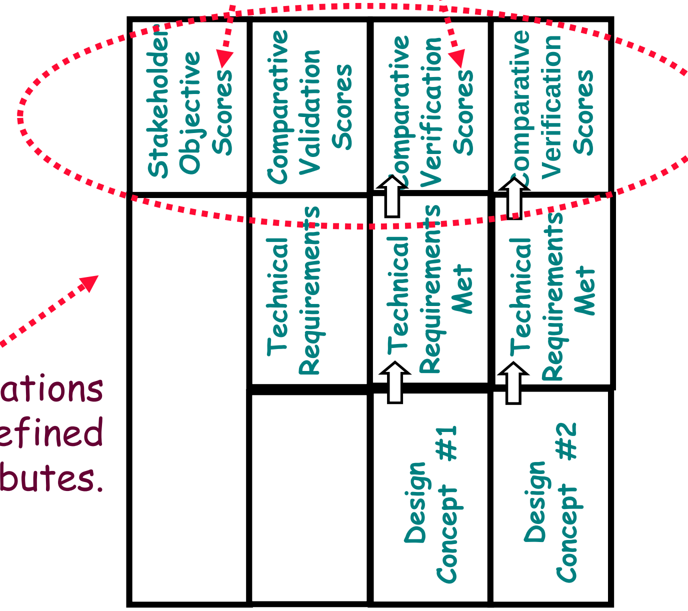
Microsoft Excel - Oil Filter Pattern V1.1.1.xls

I12 — The feature of providing services with a specified level of reliability over the normal operating life of a system.

	Feature Name	Config Rule Ref for Population	Feature Definition	Feature Attribute	PK	Attribute Definition	Attribute Units	Attribute Values	Featu Statu
2	Engine Lubricant Filtration Feature	Mandatory	The feature of maintaining a lubricating fluid at a required level of cleanliness while it is in service in a specified application, including the removal of contaminants associated with the application.	Service Application	X	The type of lubricated system application supported by a lubricant filtration system. More than one type may be instantiated for a single product configuration.	N/A	Consumer Automotive, Commercial Automotive, Fixed Base Engine System, Harsh Environment, High Thermal Environment, Cold Environment	Namec
3	Engine Lubricant Filtration Feature			Lubricant Type		The type of lubricating fluid to be used.	N/A	0	Namec
4	Engine Lubricant Filtration Feature			Lubricant Flow Rate		The rate at which the lubricating fluid must be circulated in order to meet equipment lubrication objectives.	N/A	High, Medium, Low	Namec
5	Engine Lubricant Filtration Feature			Lubricant Pressure Range		The amount of hydraulic pressure under which the lubricant will circulate.	N/A	High, Medium, Low	Namec
6	Engine Lubricant Filtration Feature			Filter Efficiency Class		The range of filtration efficiency provided by the filter	N/A	0	Namec
7	Mechanical Compatiblity Feature	Mandatory	The feature of being compatible in form factor and mechanical interface with the system in which the system will be installed.	Mechanical Interface Type		The mechanical form of an interface.	N/A	0	Namec
8	Mechanical Compatiblity Feature			Spatial Form Factor		The three dimensional structure of a component, subsystem, or space within a system reserved for a component or subsystem.	N/A	0	Namec
9	Cost of Operation Feature	Mandatory	The feature of supporting cost-effective lubrication of an application, by minimizing the cost of lubrication consumables per operating hour.	Lubricant Life		The amount of time, in operating hours, that a lubricant is intended to operate, meeting requirements within the specified environment, before it is replaced.	N/A	Standard, Long Life	
10	Cost of Operation Feature			Service Life		The amount of time, in operating hours, that a lubricant filter is intended	N/A	Standard, Long Life	



Alternate designs, different configurations, and technology generations are all ultimately "Scored" in lower-dimension trade-off space defined by the Stakeholder Feature Attributes.



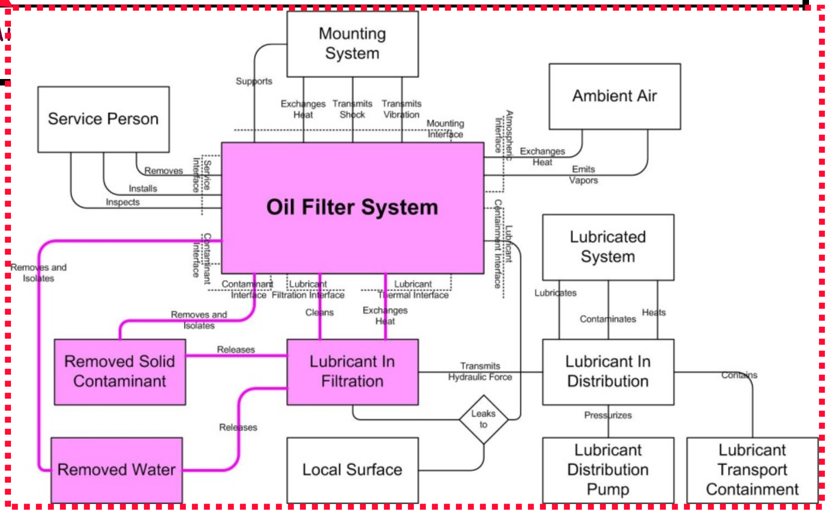
Configuration Score Sheet

For example: Every FMEA (Failure Mode Effects Analysis) failure impact can be expressed in terms of Feature Attributes.

Functional Interaction Models a key SE challenge by discovering and describing all external interactions of a Subject System. This leads to all functional requirements and thereafter all other requirements, in the Detail Requirements Model.

Product Functional Interactions, Roles

Functional Interaction	Functional Roles
Filter Lubricant	Lubricant in Filtration, Oil Filter System, Removed Solid Contaminant, Removed Water
Install Filter	Service Person, Filter
Monitor Filter	Filter, Monitor & Control System
Prevent Vapor Leakage	Lubricant, Vapor, Filter, Atmosphere
Prevent Lubricant Leakage	Lubricant, Filter, Local Surface
Transmit Shock & Vibration	Filter, Mounting System
Transmit Thermal Energy	Filter, Lubricant, Mounting System, Ambient Ai

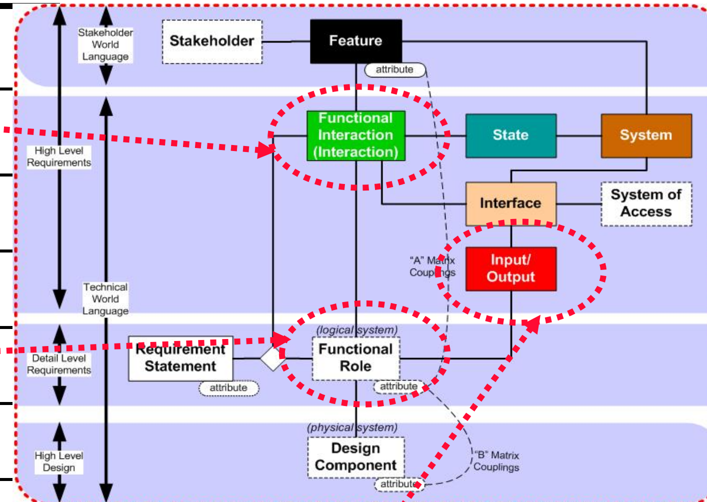


Every system directly interacting with the Subject System (Oil Filter System) contributes to its Requirements.

An Interaction of Systems, expressed as an external (outcome) relationship in which systems impact each other's states. Interacting systems fill Roles in the Interaction. Interactions technically characterize (model) the behaviors summarized by stakeholder-valued Features.

Product Functional Interactions, Roles

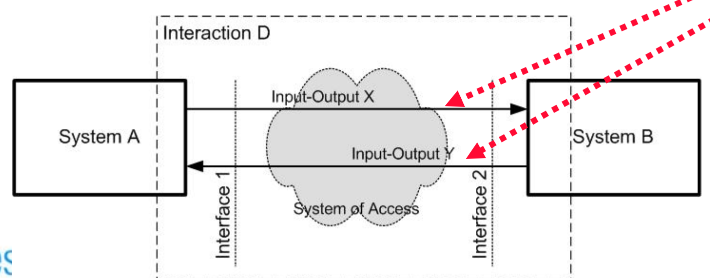
Functional Interaction	Functional Roles
Filter Lubricant	Lubricant in Filtration, Oil Filter System, Removed Solid Contaminant, Removed Water
Change Filter	Service Person, Filter
Monitor Filter	Filter, Monitor & Control System
Prevent Vapor Leakage	Lubricant, Vapor, Filter, Atmosphere
Prevent Lubricant Leakage	Lubricant, Filter, Local Surface
Transmit Shock & Vibration	Filter, Mounting System
Transmit Thermal Energy	Filter, Lubricant, Mounting System, Ambient Air



Input/Outputs exchanged during these interactions are:

- Energy
- Force
- Mass
- Information

Interactions involve two or more systems.

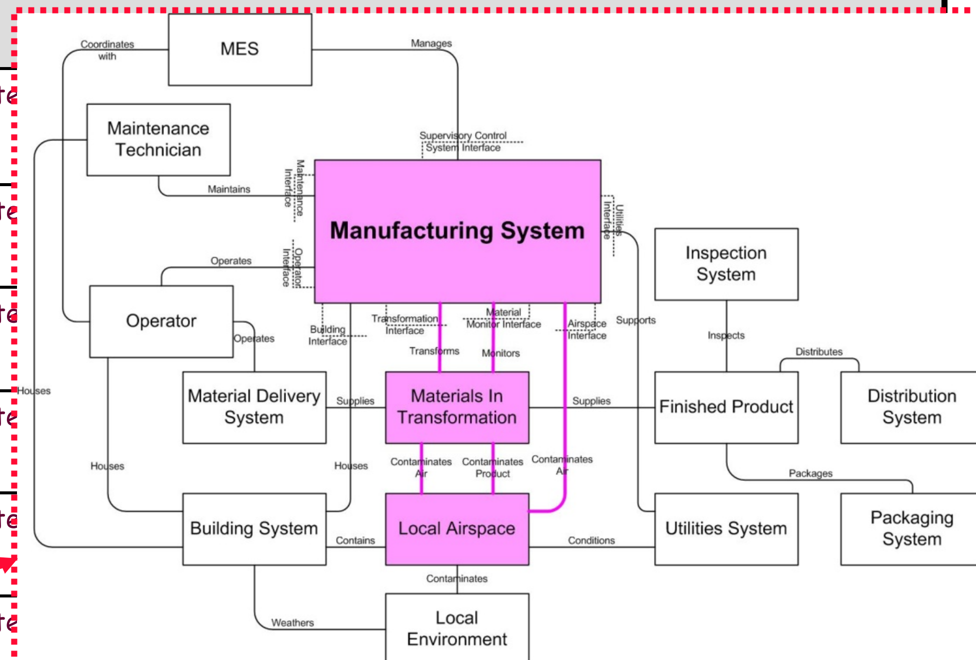


ICTT System Sciences

An Interaction of Systems, expressed as an external (outcome) relationship in which systems impact each other's states. Interacting systems fill Roles in the Interaction. Interactions technically characterize (model) the behaviors summarized by stakeholder-valued Features.

Manufacturing Functional Interactions

Functional Interaction	Functional Roles
Impregnate Lubricant Additive	Manufacturing Syste
Fold Accordion Pleats	Manufacturing Syste
Cut & Separate Filter	Manufacturing Syste
Roll Filter Element	Manufacturing Syste
Wind Filter Element	Manufacturing Syste
Insert Filter Element	Manufacturing Syste
Perform End Seal Bonding	Manufacturing System, Materials In Transformation, Local Airspace



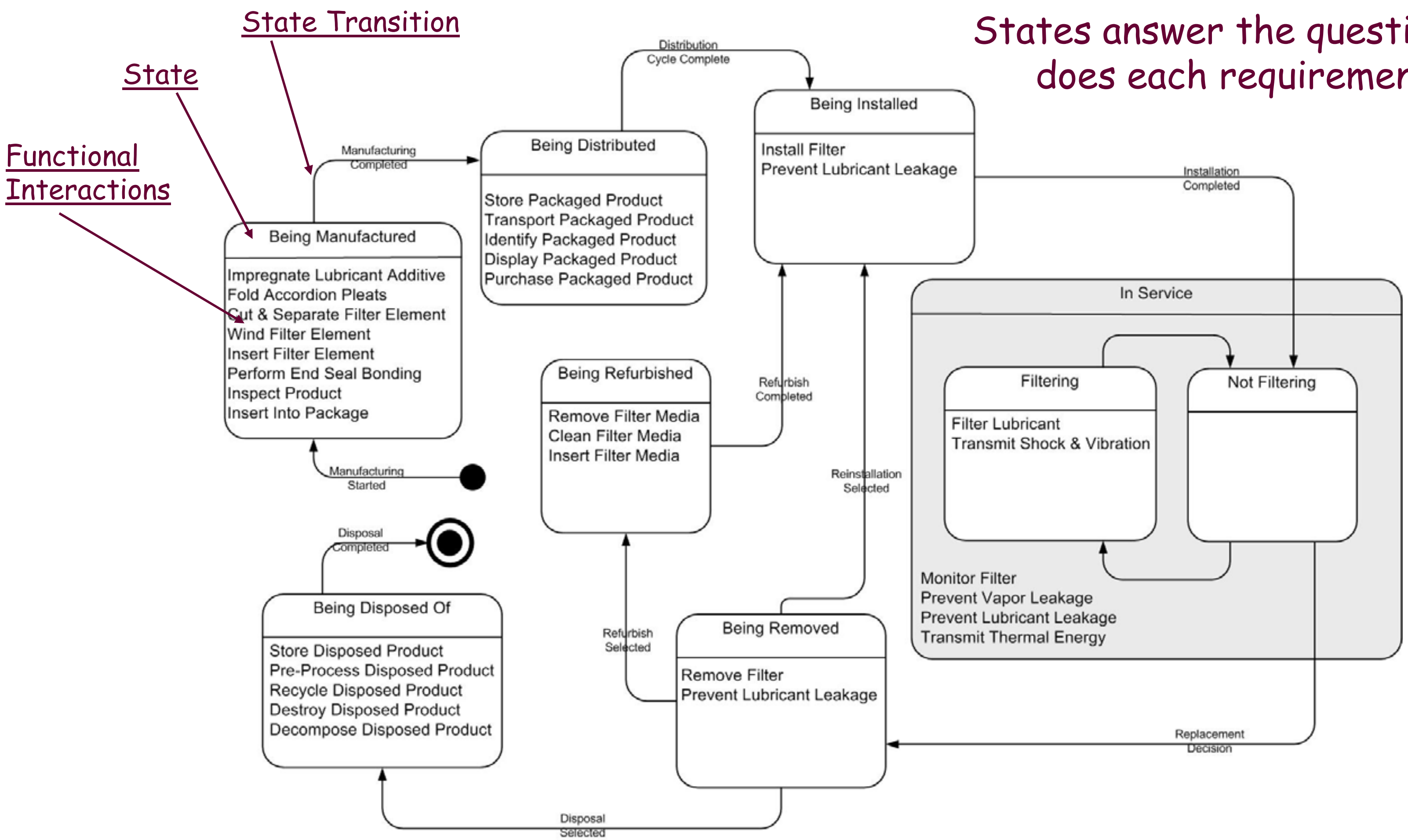
Later "drilled down" in Detail Level Requirements Model, to obtain Requirements Statements.

ICTT System Sciences

State Models directly address a key SE challenge by discovering and describing all Situations, Modes, or Use Cases (environmental states) that a Subject System will encounter. These are associated with Functional Interactions that lead directly to requirements. State Models can also describe Designs.

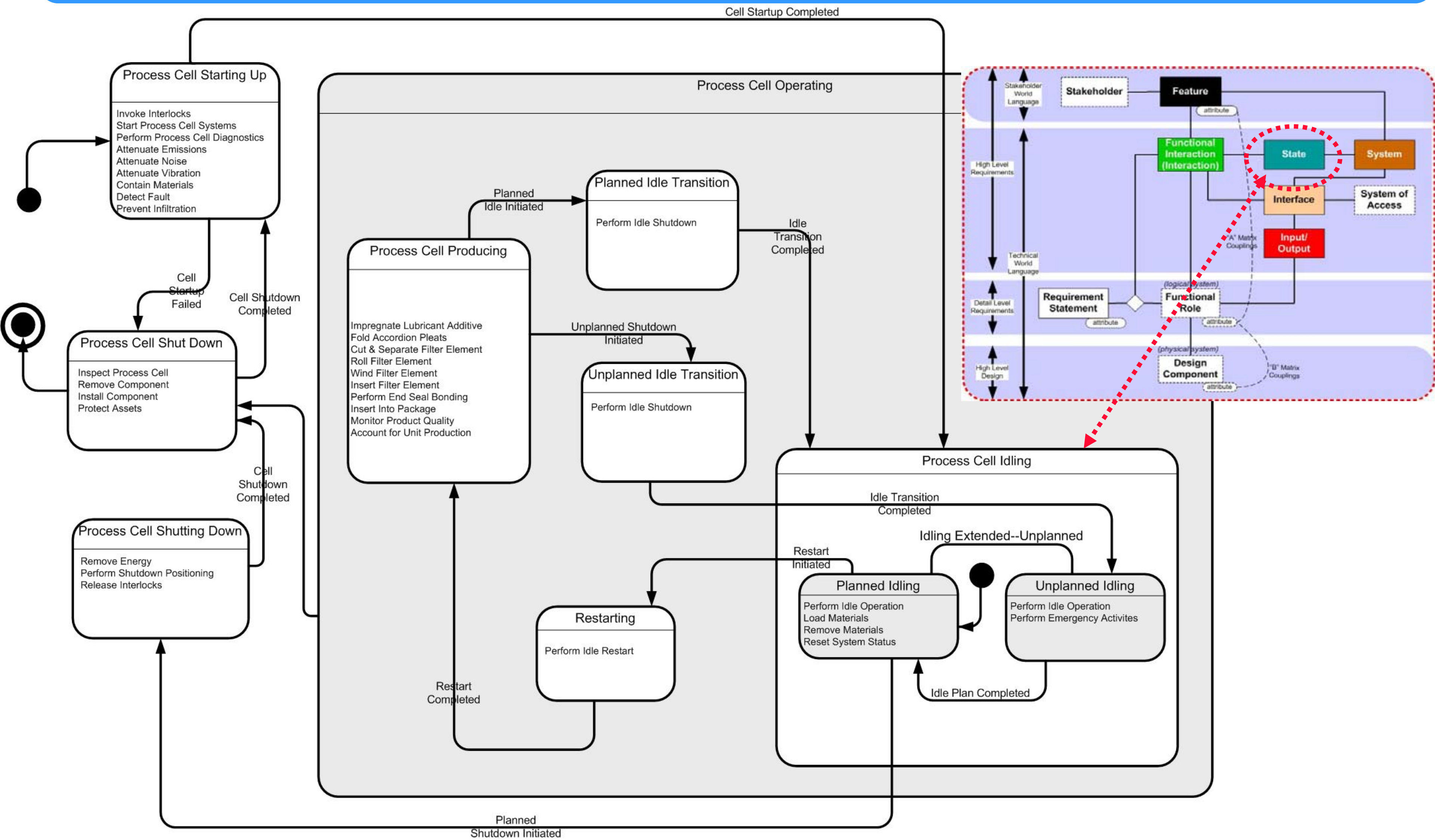
Product State Model

States answer the question: "When does each requirement apply?"



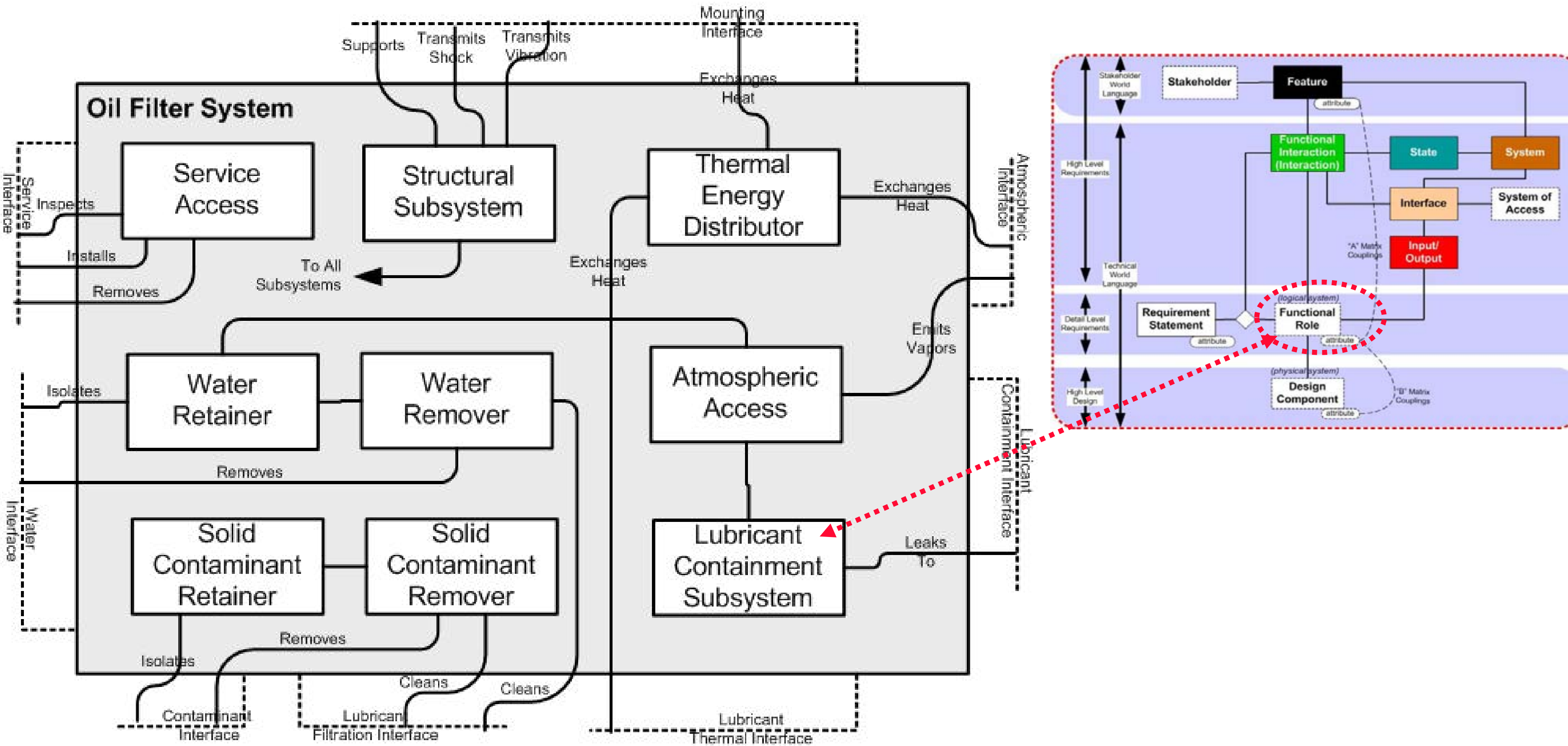
States are Situations (Modes, Use Cases, Phases) that will be encountered in the environment of a Subject System, in which it is required to meet certain requirements.

Manufacturing System State Model



Logical Architecture Models directly address key SE challenges by partitioning the structure of requirements into Logical Roles independent of design, then address more SE challenges by stimulating design ideation and role allocation to physical designs and future technologies.

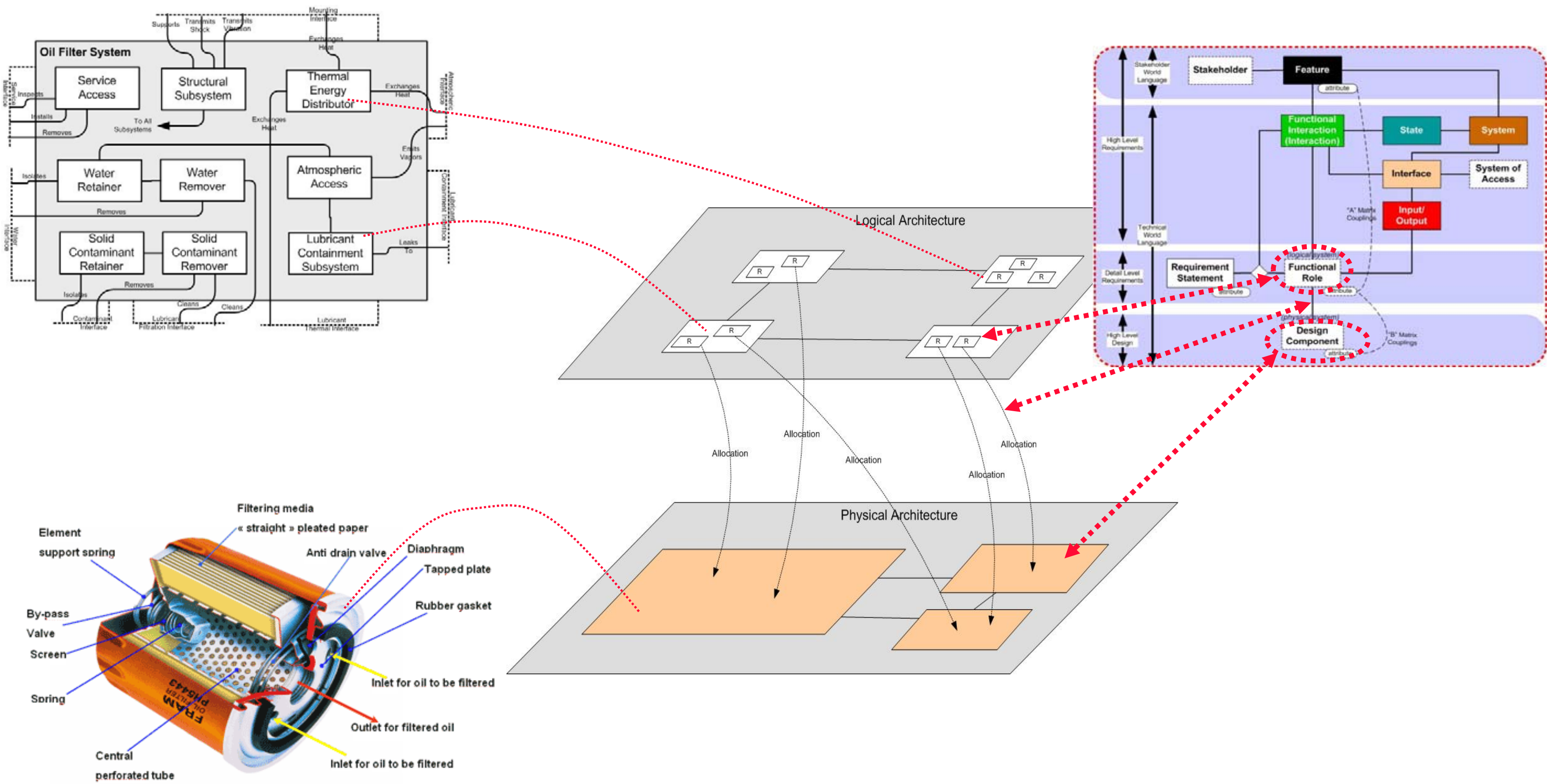
Product Logical Architecture Model



ICTT System Sciences

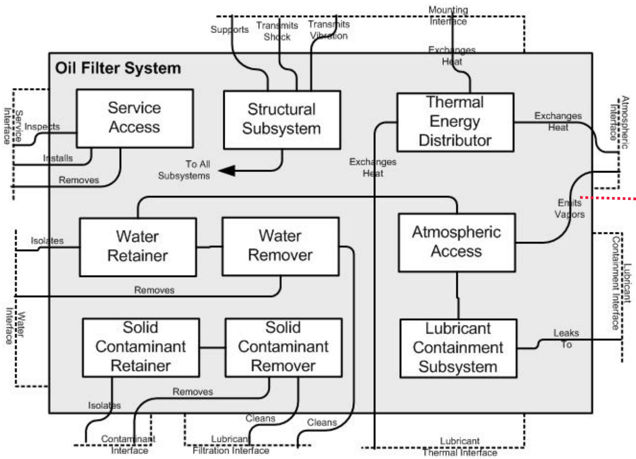
Logical roles are subsets of system behavior that formally model subsystems even though they have not been allocated yet to physical designs.

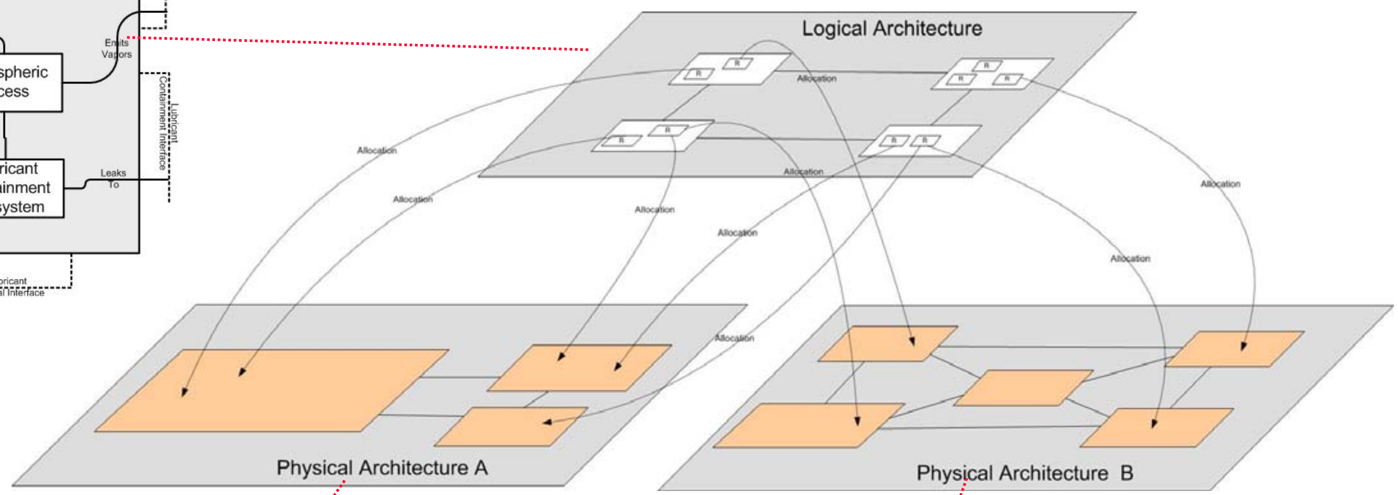
Allocating Logical Architecture to Physical Architecture

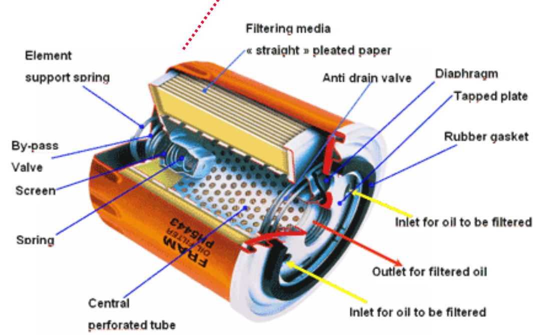


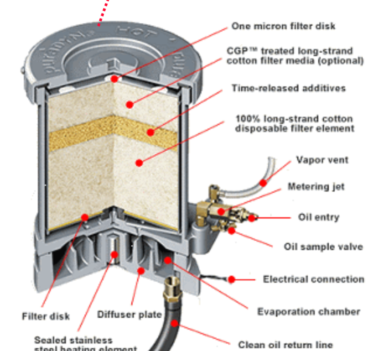
Directly addressing a key SE challenge, multiple alternate physical architectures are typically supported by a single Logical Architecture! This provides a powerful means for managing across Technologies & Configurations, and enhances Platform Management.

Alternate Technologies, Family Configurations, Roadmaps



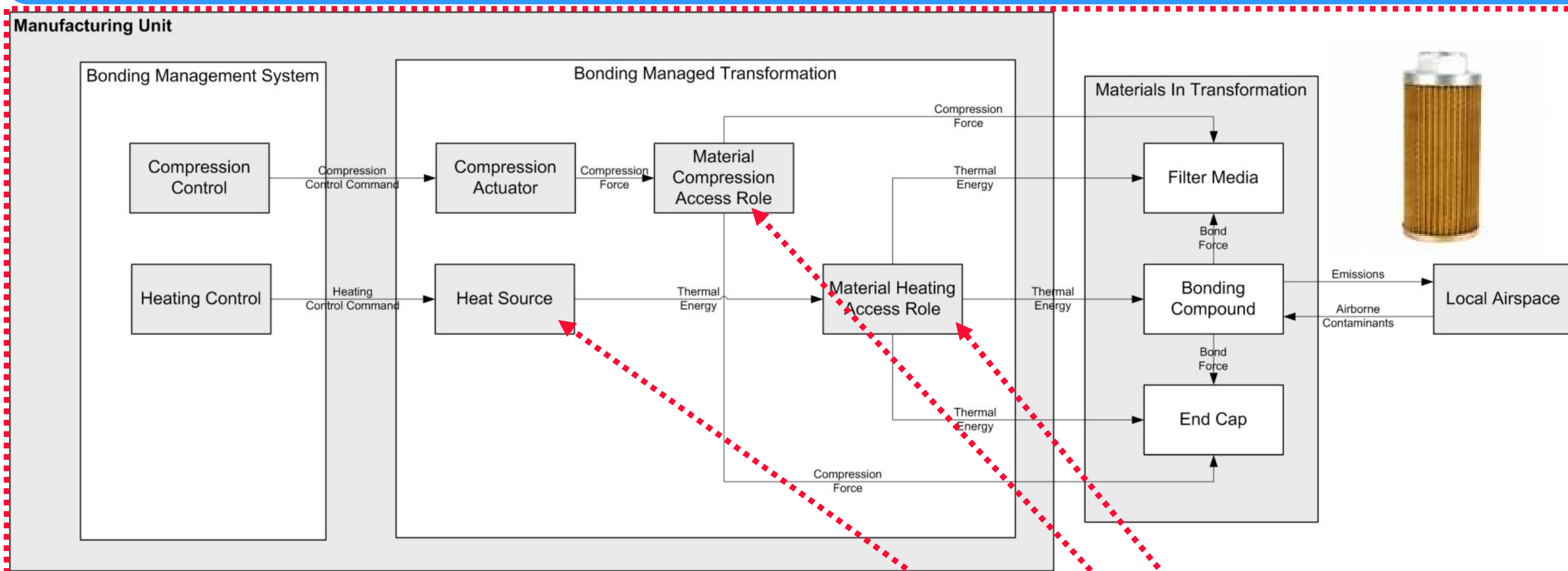






Detail Interaction Models directly address key SE challenge by providing model-based Requirements. These include Functional as well as non-Functional aspects, including all technical requirements (Role) Attributes.

Detail Interaction Models

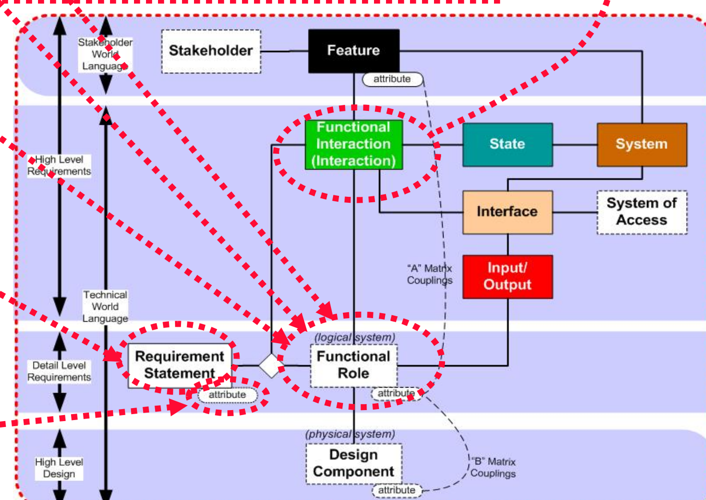


Benefit: This allows prose Requirements Statements to be viewed as Transfer Functions, greatly improving ability to audit regular detail requirements by embedding them in the Model:

Requirement OFM-32: "The Manufacturing System shall deliver a Compression Force of [Min Bond Force] for a period of [Min Bond Time]".

Requirement OFM-33: "The Manufacturing System shall deliver Thermal Energy sufficient to maintain a bond temperature of [Min Bond Temperature] for a period of [Min Bond Time]."

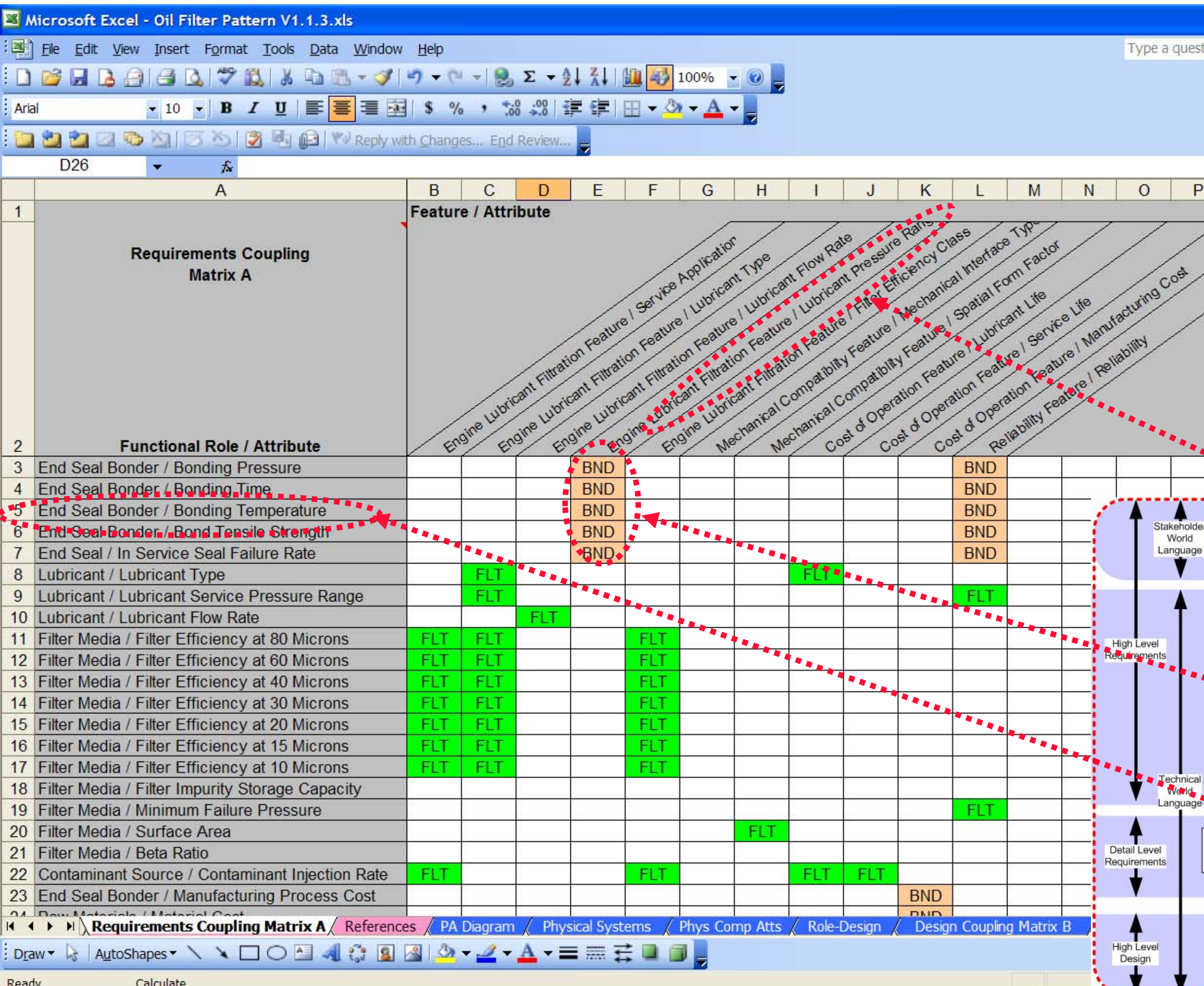
Requirement OF-51: "The Oil Filter shall operate at lubricant pressure of [Max Lubricant Pressure] with structural failure rates less than [Max Structural Failure Rate] over an in-service life of [Min Service Life]."



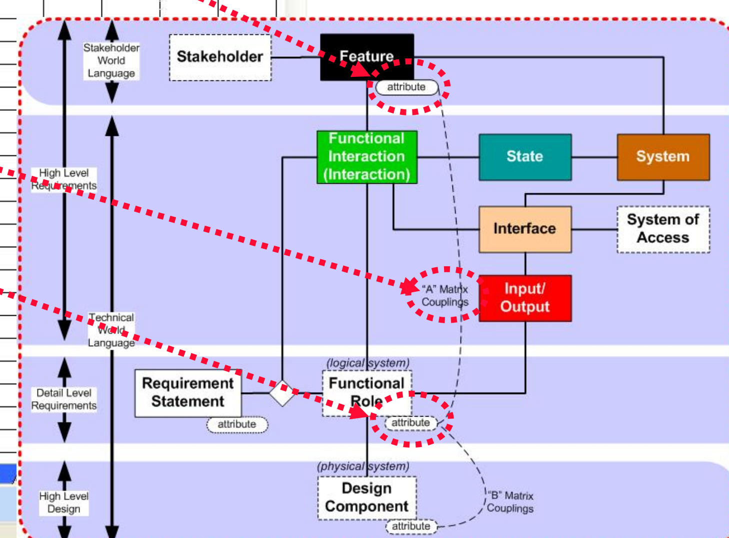
The Attribute Coupling Model addresses a key SE challenge to understand the quantitative coupling of stakeholder preferences (Features) to technical requirements (Roles), establishing a Feature-based scoring space for trade-offs.

Attribute Coupling Model--Requirements

- The "A" and "B" couplings organize all the quantitative relationships, including first principles math / physics models, design of experiment models, empirical studies, market surveys, etc.
- Organizes trade-off scoring space.
- Provides a uniform way to integrate Team Partner models of Fuel Cell, other systems.

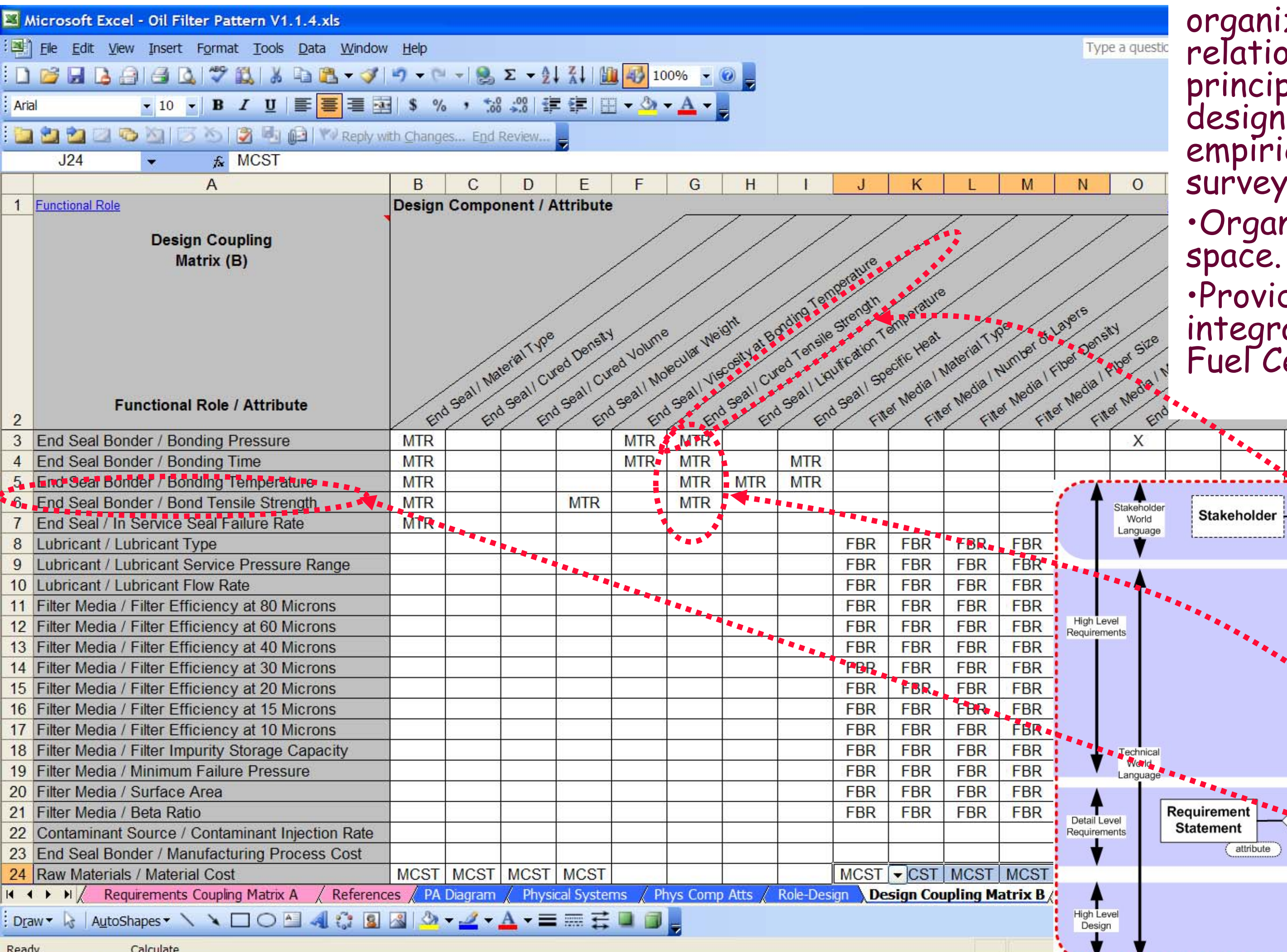


	A: Requirements Coupling Matrix A — Functional Role / Attribute	B: Engine Lubricant Filtration Feature / Service Application	C: Engine Lubricant Filtration Feature / Lubricant Type	D: Engine Lubricant Filtration Feature / Lubricant Flow Rate	E: Engine Lubricant Filtration Feature / Lubricant Pressure Rang	F: Engine Lubricant Filtration Feature / Filter Efficiency Class	G: Mechanical Compatibility Feature / Mechanical Interface Typ	H: Mechanical Compatibility Feature / Spatial Form Factor	I: Cost of Operation Feature / Lubricant Life	J: Cost of Operation Feature / Service Life	K: Cost of Operation Feature / Manufacturing Cost	L: Reliability Feature / Reliability	M	N	O	P
3	End Seal Bonder / Bonding Pressure				BND							BND				
4	End Seal Bonder / Bonding Time				BND							BND				
5	End Seal Bonder / Bonding Temperature				BND							BND				
6	End Seal Bonder / Bond Tensile Strength				BND							BND				
7	End Seal / In Service Seal Failure Rate				BND							BND				
8	Lubricant / Lubricant Type		FLT						FLT							
9	Lubricant / Lubricant Service Pressure Range		FLT									FLT				
10	Lubricant / Lubricant Flow Rate			FLT												
11	Filter Media / Filter Efficiency at 80 Microns	FLT	FLT			FLT										
12	Filter Media / Filter Efficiency at 60 Microns	FLT	FLT			FLT										
13	Filter Media / Filter Efficiency at 40 Microns	FLT	FLT			FLT										
14	Filter Media / Filter Efficiency at 30 Microns	FLT	FLT			FLT										
15	Filter Media / Filter Efficiency at 20 Microns	FLT	FLT			FLT										
16	Filter Media / Filter Efficiency at 15 Microns	FLT	FLT			FLT										
17	Filter Media / Filter Efficiency at 10 Microns	FLT	FLT			FLT										
18	Filter Media / Filter Impurity Storage Capacity															
19	Filter Media / Minimum Failure Pressure											FLT				
20	Filter Media / Surface Area							FLT								
21	Filter Media / Beta Ratio															
22	Contaminant Source / Contaminant Injection Rate	FLT				FLT			FLT	FLT						
23	End Seal Bonder / Manufacturing Process Cost										BND					



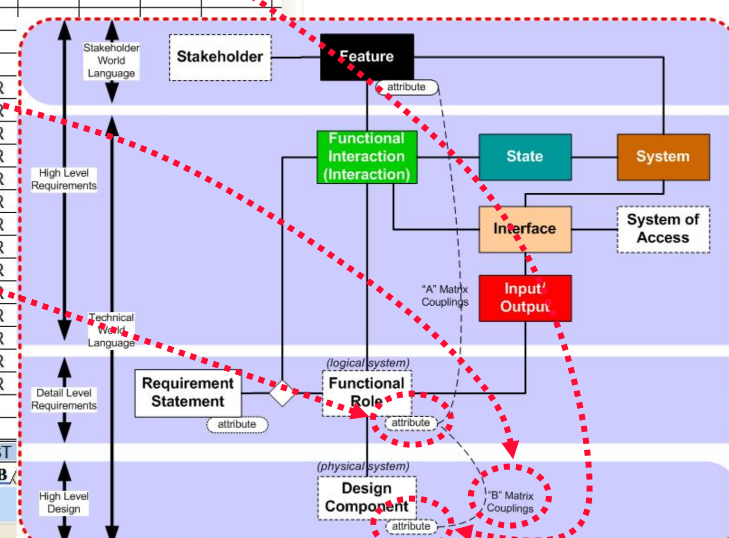
The Attribute Coupling Model addresses a key Challenge to describe the coupling of Design Component attributes to technical requirements (Role) attributes, provide scoring (in Feature Space) of Design Attribute solutions.

Attribute Coupling Model--Designs

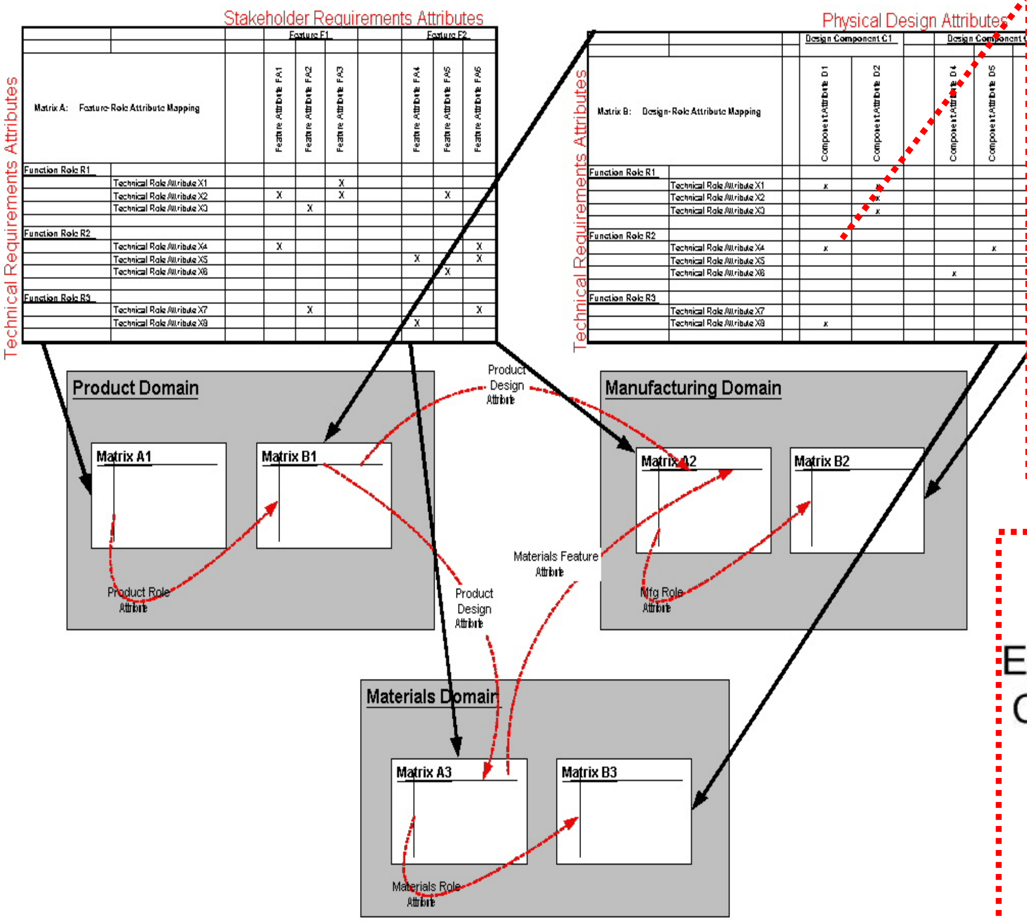


	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	Functional Role	Design Component / Attribute													
2	Design Coupling Matrix (B) / Functional Role / Attribute	End Seal / Material Type	End Seal / Cured Density	End Seal / Cured Volume	End Seal / Molecular Weight	End Seal / Viscosity at Bonding Temperature	End Seal / Cured Tensile Strength	End Seal / Liquification Temperature	End Seal / Specific Heat	Filter Media / Material Type	Filter Media / Number of Layers	Filter Media / Fiber Density	Filter Media / Fiber Size	Filter Media / M	End
3	End Seal Bonder / Bonding Pressure	MTR				MTR	MTR								X
4	End Seal Bonder / Bonding Time	MTR				MTR	MTR		MTR						
5	End Seal Bonder / Bonding Temperature	MTR					MTR	MTR	MTR						
6	End Seal Bonder / Bond Tensile Strength	MTR			MTR		MTR								
7	End Seal / In Service Seal Failure Rate	MTR													
8	Lubricant / Lubricant Type									FBR	FBR	FBR	FBR		
9	Lubricant / Lubricant Service Pressure Range									FBR	FBR	FBR	FBR		
10	Lubricant / Lubricant Flow Rate									FBR	FBR	FBR	FBR		
11	Filter Media / Filter Efficiency at 80 Microns									FBR	FBR	FBR	FBR		
12	Filter Media / Filter Efficiency at 60 Microns									FBR	FBR	FBR	FBR		
13	Filter Media / Filter Efficiency at 40 Microns									FBR	FBR	FBR	FBR		
14	Filter Media / Filter Efficiency at 30 Microns									FBR	FBR	FBR	FBR		
15	Filter Media / Filter Efficiency at 20 Microns									FBR	FBR	FBR	FBR		
16	Filter Media / Filter Efficiency at 15 Microns									FBR	FBR	FBR	FBR		
17	Filter Media / Filter Efficiency at 10 Microns									FBR	FBR	FBR	FBR		
18	Filter Media / Filter Impurity Storage Capacity									FBR	FBR	FBR	FBR		
19	Filter Media / Minimum Failure Pressure									FBR	FBR	FBR	FBR		
20	Filter Media / Surface Area									FBR	FBR	FBR	FBR		
21	Filter Media / Beta Ratio									FBR	FBR	FBR	FBR		
22	Contaminant Source / Contaminant Injection Rate														
23	End Seal Bonder / Manufacturing Process Cost														
24	Raw Materials / Material Cost	MCST	MCST	MCST	MCST					MCST	CST	MCST	MCST		

- The “A” and “B” couplings organize all the quantitative relationships, including first principles math / physics models, design of experiment models, empirical studies, market surveys, etc.
- Organizes trade-off scoring space.
- Provides a uniform way to integrate Team Partner models of Fuel Cell, other systems.

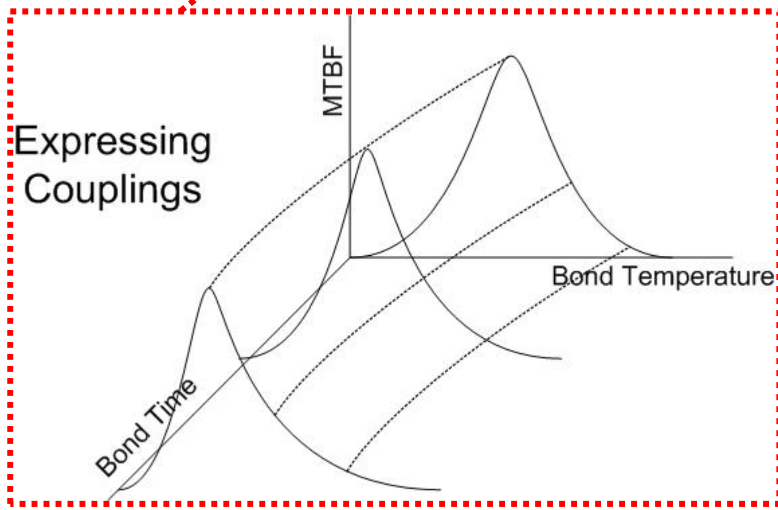


Attribute couplings cross domains



The Coupling Model is a unifying framework integrating all forms of coupling:

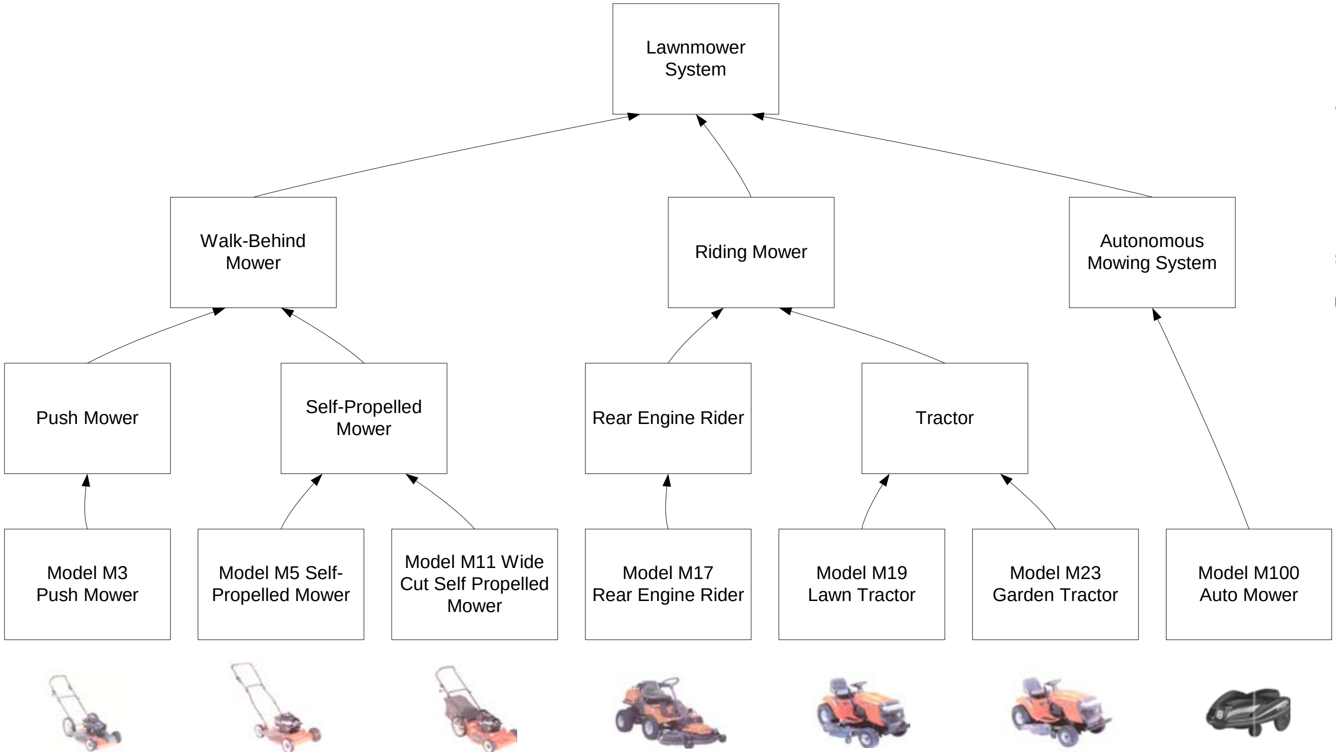
- First principles equations
- Empirical datasets
- Graphical relations
- Data tables
- Prose statements
- Fuzzy relationships
- Other

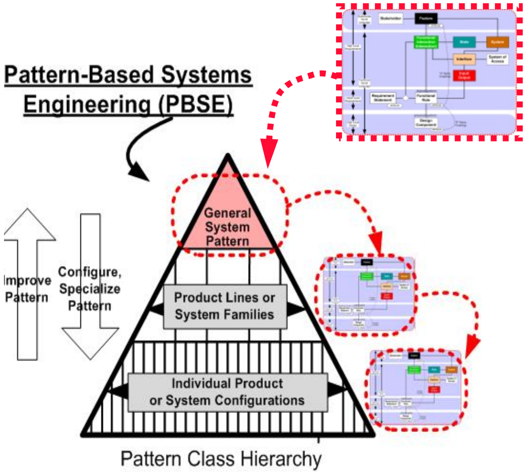


The Family Configurations Model directly addresses a key SE challenge by providing Class Hierarchy Models with Configuration Rules (Gestalt Rules) that govern Platforms and Portfolios of Products, Systems, and Technologies.

Family Configurations Model

- The Family Configurations Model supports multiple configurations, technologies:

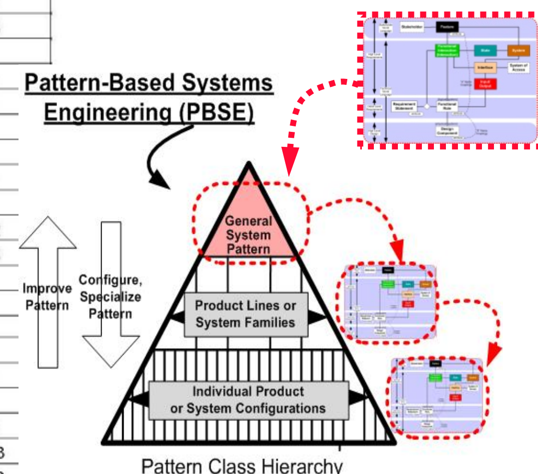




- This can be exploited by partitioning the model to integrate with existing Portfolio Roadmaps for Markets, Technologies, and Products

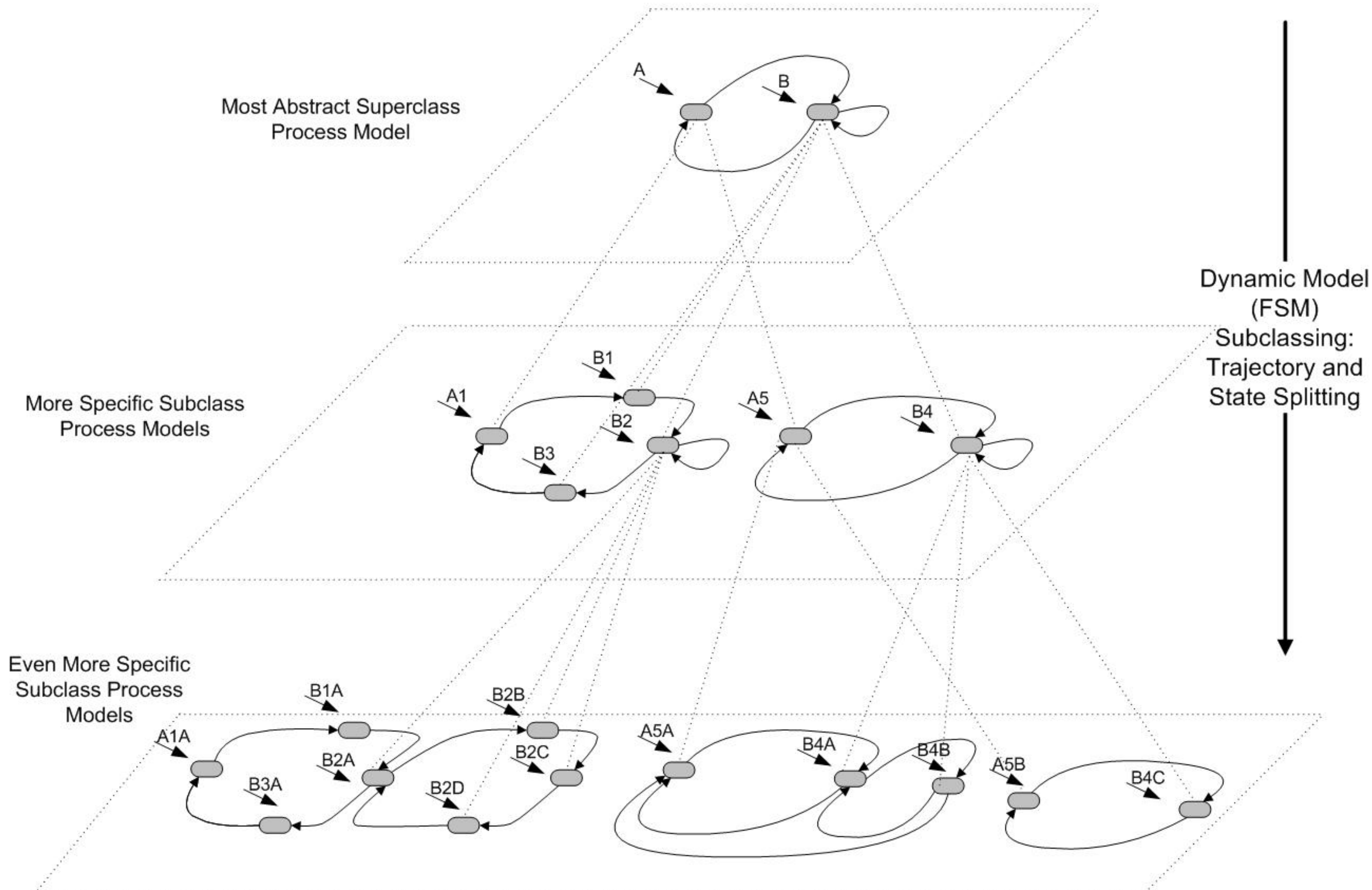
Family Configurations Model

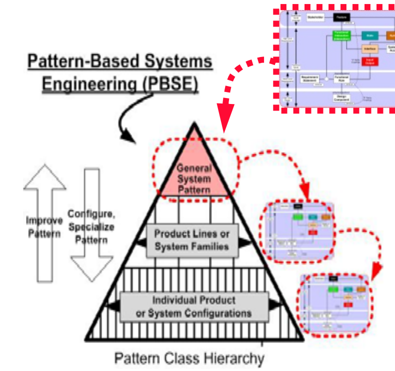
Lawnmower Product Line: Configurations Table									
		Units							
			Walk-Behind Mower	Walk-Behind Mower	Walk-Behind Mower	Riding Mower	Riding Mower	Riding Mower	Autonomous Mowing System
			Push Mower	Self-Propelled Mower	Self-Propelled Mower	Rear Engine Rider	Tractor	Tractor	Autonomous Mowing System
			Push Mower	Self-Propelled	Wide Cut Self Propelled Mower	Rear Engine Rider	Lawn Tractor	Garden Tractor	Auto Mower
	Model Number		M3	M5	M11	M17	M19	M23	M100
	Market Segment		Small Residential	Medium Residential	Medium Residential	Large Residential	Large Residential	Home Garden	High End Suburban
Power	Engine Manufacturer		Briggs & Stratton	Briggs & Stratton	Tecumseh	Tecumseh	Kohler	Kohler	Elektroset
	Horsepower	HP	5	6.5	13	16	18.5	22	0.5
Production	Cutting Width	Inches	17	19	36	36	42	48	16
	Maximum Mowing Speed	MPH	3	3	4	8	10	12	2.5
	Maximum Mowing Productivity	Acres/Hr			1.6				
	Turning Radius	Inches	0	0	0	0	126	165	0
	Fuel Tank Capacity	Hours	1.5	1.7	2.5	2.8	3.2	3.5	2
	Towing Feature						x	x	
	Electric Starter Feature				x	x	x	x	
	Basic Mowing Feature Group		x	x	x	x	x	x	x
Mower	Number of Anti-Scalping Rollers		0	0	1	2	4	6	0
	Cutting Height Minimum	Inches	1	1.5	1.5	1.5	1	1.5	1.2
	Cutting Height Maximum	Inches	4	5	5	6	8	10	3.8
	Operator Riding Feature					x	x	x	
	Grass Bagging Feature		Optional	Optional	Optional	Optional	Optional	Optional	
	Mulching Feature		Standard	Factory Installed	Dealer Installed				
	Aerator Feature					Optional	Optional	Optional	
	Autonomous Mowing Feature								x
	Dethatching Feature					Optional	Optional	Optional	
Physical	Wheel Base	Inches	18	20	22	40	48	52	16
	Overall Length	Inches	18	20	23	58	56	68	28.3
	Overall Height	Inches	40	42	42	30	32	36	10.3
	Width	Inches	18	20	22	40	48	52	23.6
	Weight	Pounds	120	160	300	680	705	1020	15.6
	Self-Propelled Mowing Feature			x	x	x	x	x	x
	Fully Automatic Transmission Feature							x	
Financials	Retail Price	Dollars	360	460	1800	3300	6100	9990	1799
	Manufacturer Cost	Dollars	120	140	550	950	1800	3500	310
Maintenance	Warranty	Months	12	12	18	24	24	24	12
	Product Service Life	Hours	500	500	600	1100	1350	1500	300
	Time Between Service	Hours	100	100	150	200	200	250	100
Safety	Spark Arrest Feature		x	x	x	x	x	x	



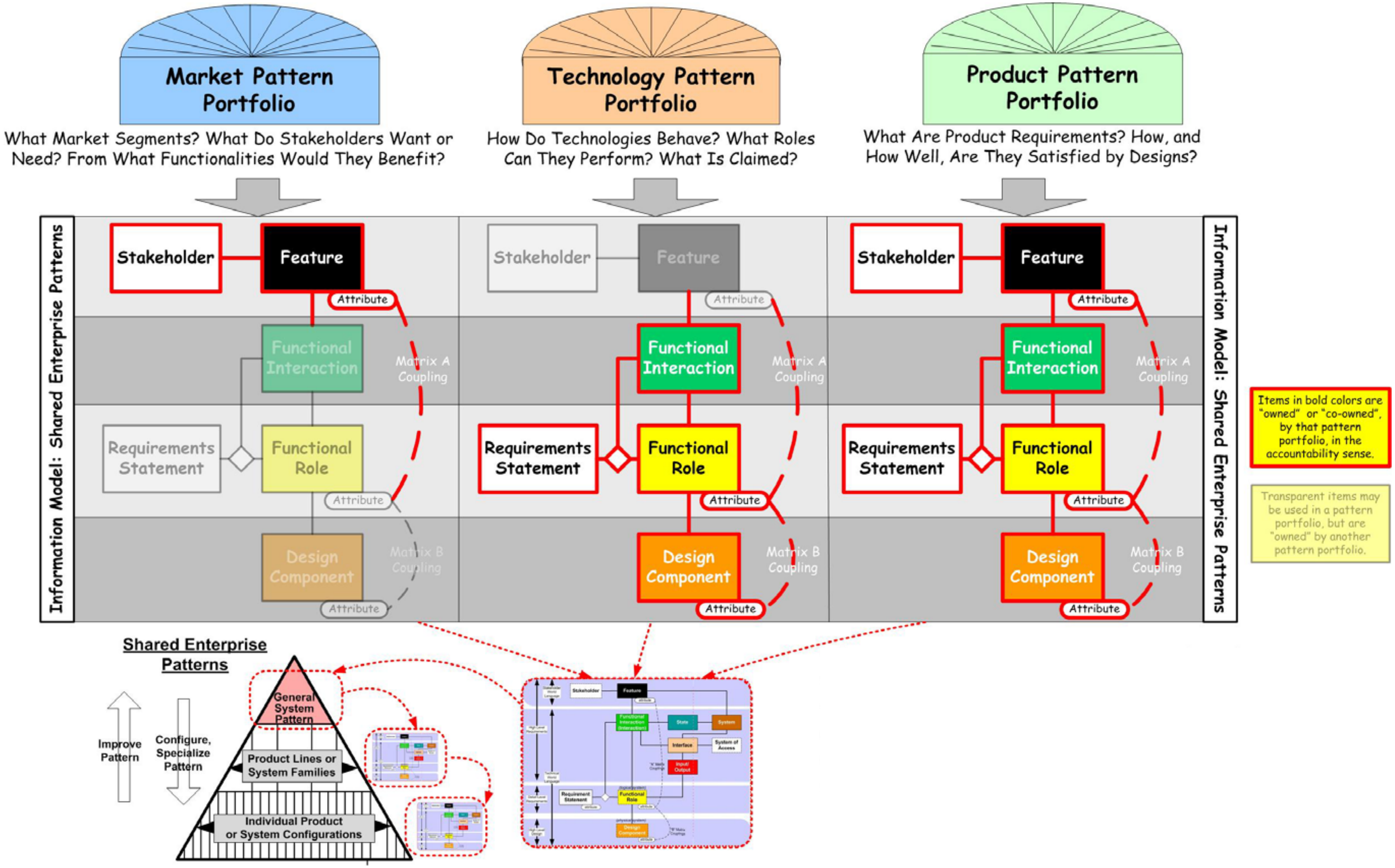
Family Configurations Model

Class Hierarchy of Dynamic Process Models (Finite State Machines)

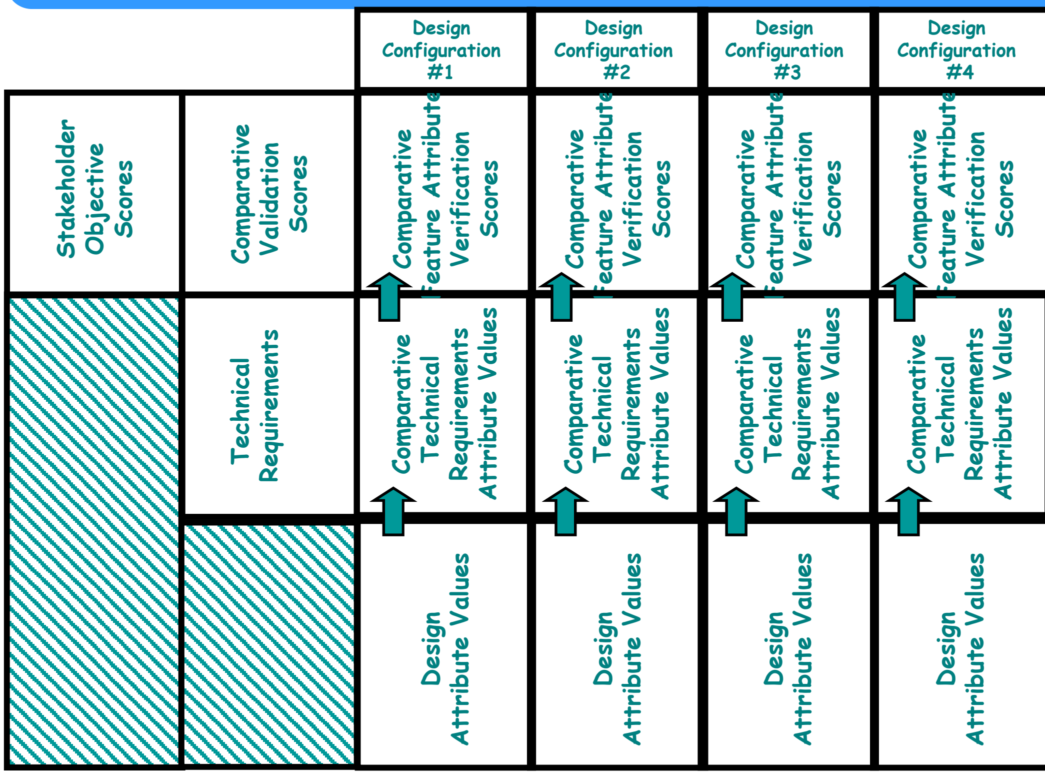


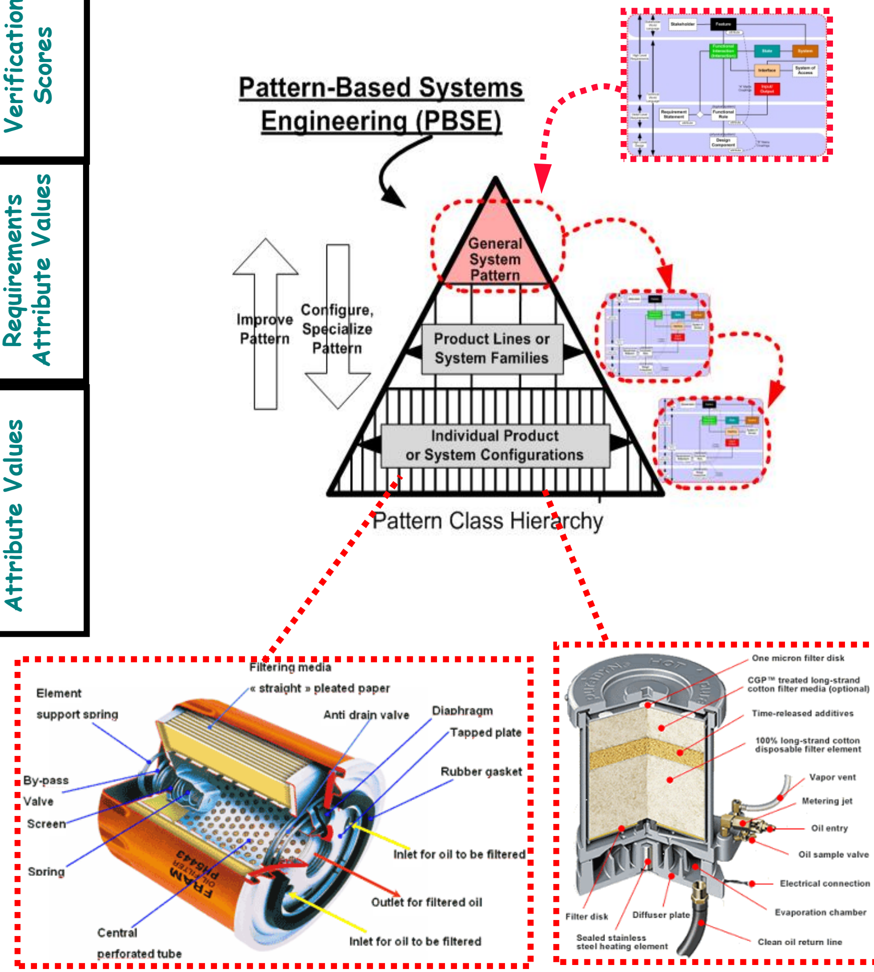


Family Configurations Model



Scoring across configurations



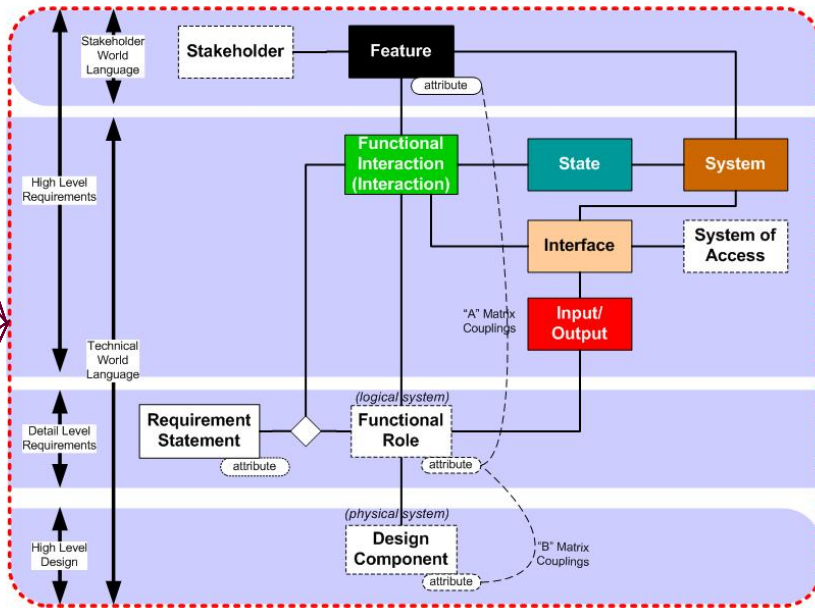


The preceding multiple SE challenges are all addressed from a single, consistent, underlying Model/Pattern information model. This reduces effort to produce consistent, auditable Model Views.

Extracts from Underlying Model

Individual model views address the listed challenges from a consistent underlying base of information

- Product and Manufacturing Domain Models
- Stakeholder Feature Models
- Product and Manufacturing Interactions Models
- Product and Manufacturing State Models



- Product and Manufacturing Family Configurations Models
- Product and Manufacturing Detailed Interactions Models
- Product and Manufacturing Logical Architecture Models
- Product and Manufacturing Attribute Coupling Models

Implications for discussion

- Model-Based Systems Engineering (MBSE) Metamodel provides:
  - an information framework organizing and integrating all requirements and design information--combining partner and other source models;
  - Integrates across Product Application, Manufacturing, and other Domain Systems -- facilitates finding where the "holes" are;
  - Explicates decision-making criteria in Stakeholder Feature trade-off configuration space;
  - Unifies mathematical and prose requirements, design constraints.
- Pattern-Based Systems Engineering (PBSE):
  - Applies and extends the MBSE metamodel to describe Patterns of requirements and designs;
  - These can represent product platforms with configurable options;
  - They can also represent consistent Market Portfolios, Technology Portfolios, and Product Portfolios, all of which are dynamically changing;
  - PBSE is inherently enabled by starting to perform MBSE.

For additional information

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