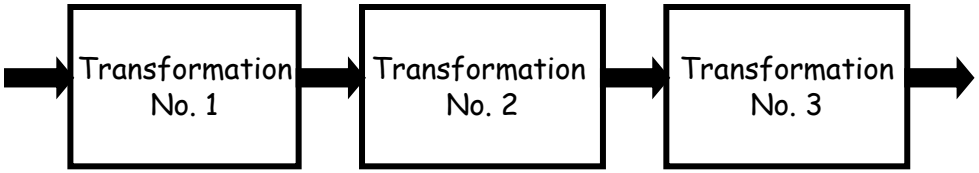
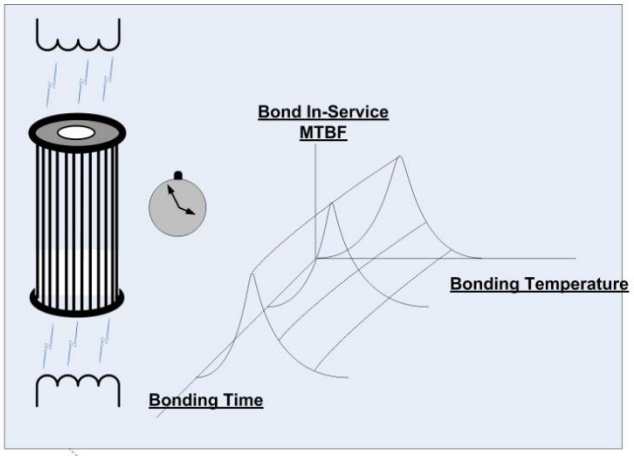
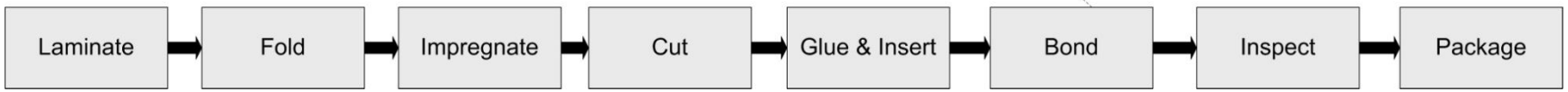
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Systems Engineering for Manufacturing Systems: Insights from Model-Based SE Methods

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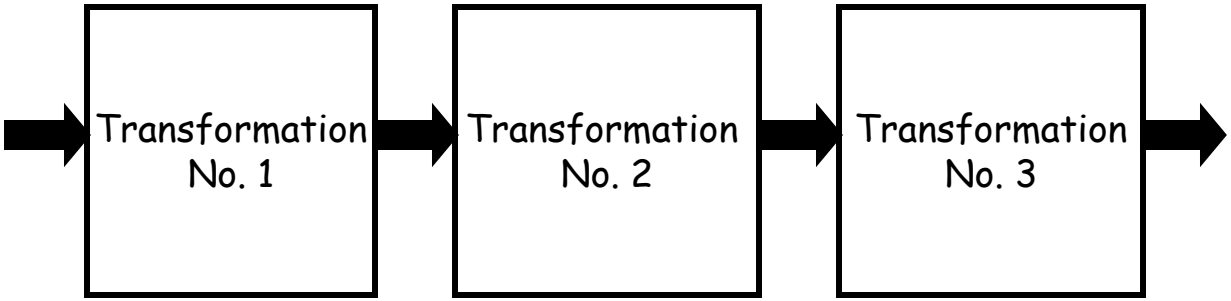
- Systems Engineering for manufacturing systems:
  - The Process Engineer's perspective
  - Integration with the larger engineering context: Challenges
- Integrating a science-based understanding
  - How the physical sciences inform model-based engineering methods
- Model-Based Systems Engineering (MBSE)
  - Brief overview
- Using MBSE to address Manufacturing Process challenges
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  - Summary of procedure
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- Additional information
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The Process Engineer's Perspective

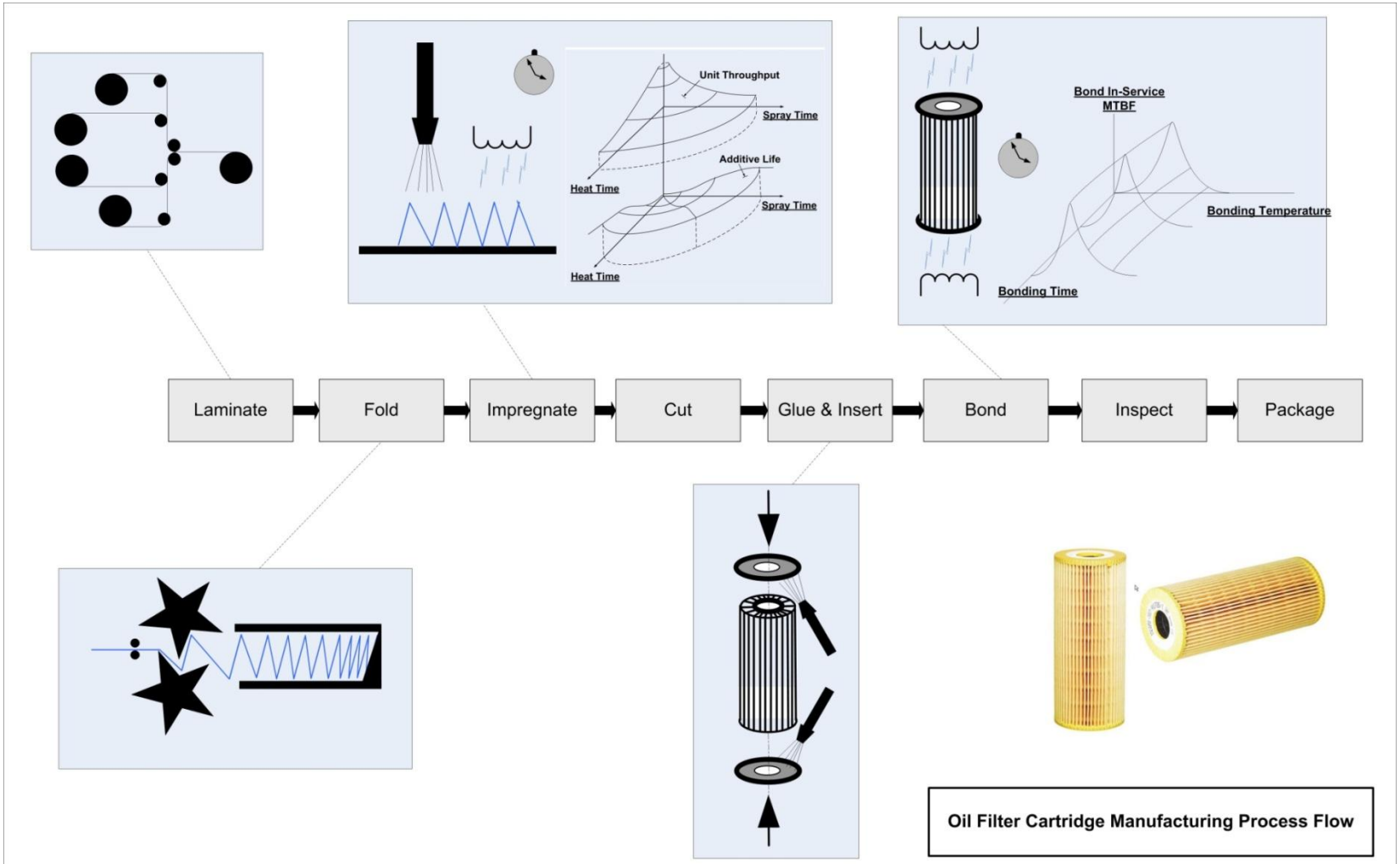
- Process Engineers are trained to visualize manufacturing as transformations of material (or of information).
- This is frequently represented graphically using Process Flow Diagrams (PFDs):



- The material flowing out is different than the material flowing in--it is "transformed" chemically, structurally, thermodynamically, as information, visually, etc.

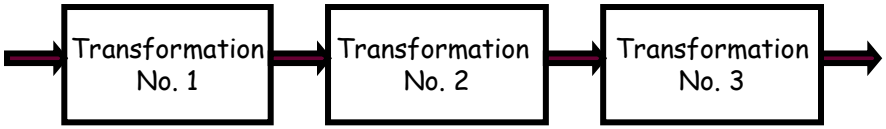
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A Simple Example: Manufacturing Oil Filter Cartridges



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Process Engineering vs. Equipment Design



- By omitting equipment-specific design, the PFD perspective has the advantage of emphasizing what is required to be changed (transformed) about the material, without describing how manufacturing equipment, tools, people, or control systems will accomplish those transformations:



- Since it describes the required transformations, it is a form of requirements on a manufacturing system.

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Process Engineering Challenges

- Process Engineering and Process Flow Diagrams provide powerful tools for conceptualizing manufacturing processes.
- However, the fact they use a perspective or language separate from design of equipment requires that the enterprise bridge a gap when integrating PE into the larger engineering context.
- For example, not all requirements on a manufacturing system are requirements of the process itself—they may even conflict.
- Various enterprises and trade groups have wrestled with the question of integrating the larger engineering process for manufacturing systems . . .

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Integration with the larger engineering context: Challenges

1. How can the language and perspective of process engineers be more effectively coupled to those of equipment designers?
2. How do process requirements fit into overall manufacturing system requirements, which have larger scope?
3. What is the relationship of physical equipment design to these requirements?
4. How can process requirements for new or modified products be incorporated early enough in the equipment design cycle?
5. How are manufacturing system requirements that are not transformation of materials related to this?
6. How can we conceive new manufacturing solutions without being mentally trapped in assuming constraints of past designs?
7. How can candidate manufacturing designs, design changes, or design risks be evaluated in light of process engineering needs?
8. How are industry reference models of manufacturing (e.g., ISA, ISPE, etc.) related to these issues?
9. More generally, how can increasingly complex advanced manufacturing systems best be engineered, over their life cycles?

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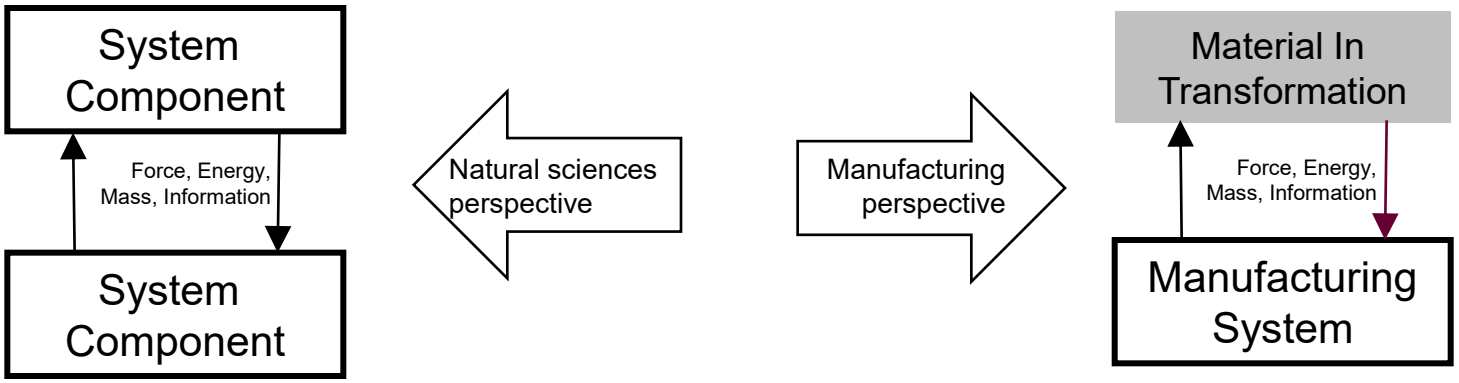
The need for a Science-based Understanding

- Industry trends increasingly emphasize science-based understanding of manufacturing processes:
  - Unit operations: key parametric relationships—materials science, chemistry, physics, etc.
  - First principle and empirical characterizations;
  - Mathematics of production flow;
  - Process capabilities and control laws;
  - Regulatory (e.g., FDA) pressures for a more science-based approach.

- How do we fit science-based understanding into an integrated framework of process and equipment engineering?

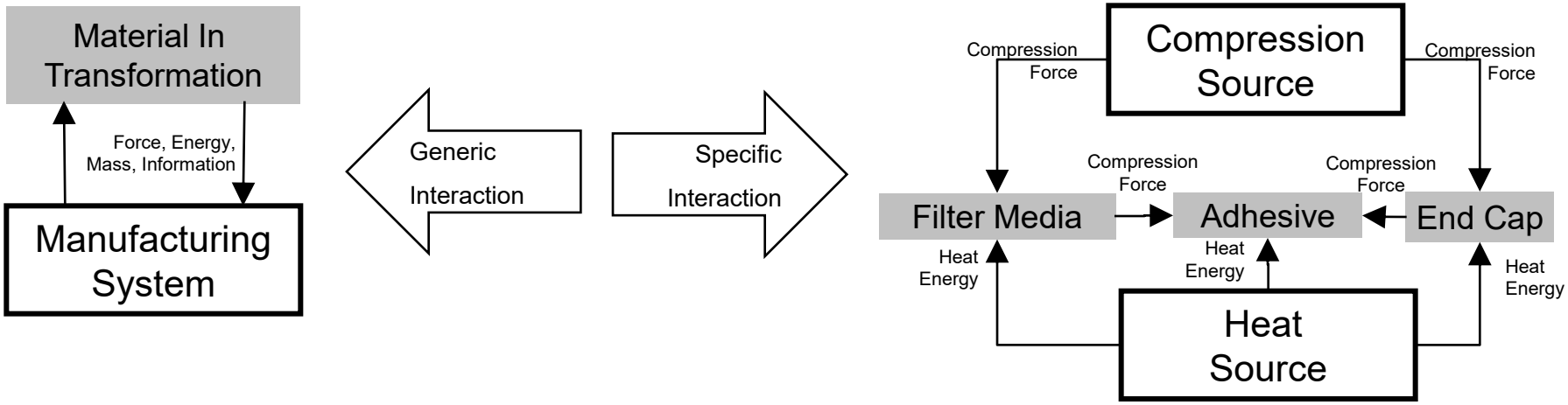
The need for a Science-based Understanding

- *Literally everything we know* from the physical sciences is about the *behavior of interacting system components*—whether in chemical reactions, electromagnetics, acoustics, mechanics, thermodynamics, or other discipline-specific interactions:



- Accordingly, the *interactions* of Materials In Transformation with the Manufacturing System assign "roles" to the *Manufacturing System* and the *Materials*, which are required to be met by what we have learned from sciences and by the results we want.

An example Interaction



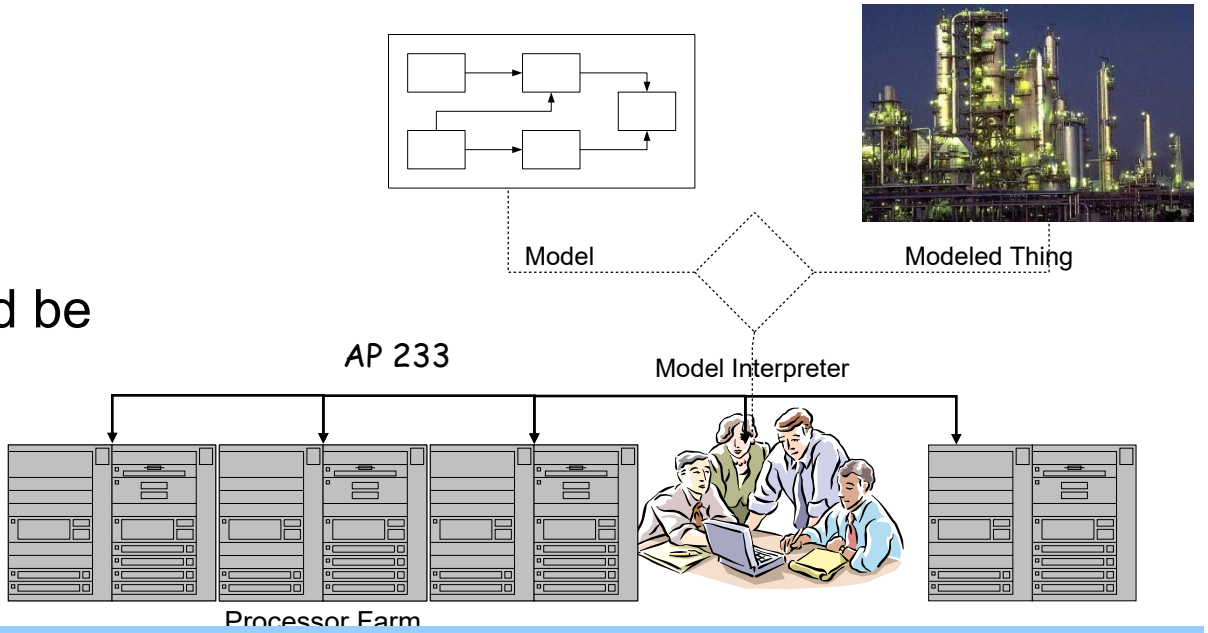
- Interaction = “Bond Filter Media to End Cap”
- Functional Roles (of materials and equipment):
  - Filter Media
  - End Cap
  - Adhesive
  - Heat Source
  - Compression Source



- Each of these “Roles” includes specific Required Behavior in order to meet expectations for the overall Interaction.
- The Physical Component to which the Role is allocated must meet those requirements—whether Equipment, Materials, or People

Model-based systems engineering (MBSE)

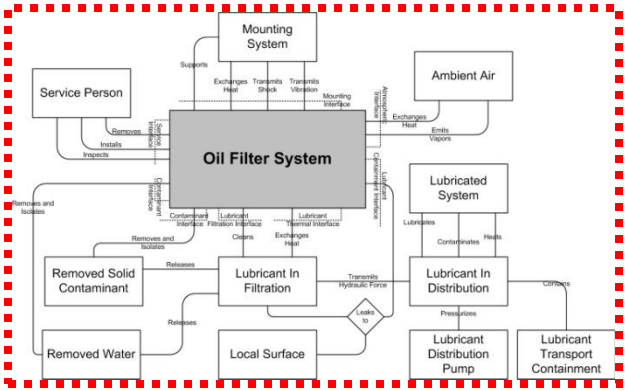
- Model-based systems engineering is an emerging approach to systems engineering:
  - See www.incose.org
- Uses explicit models where previously informal, intuitive, natural language prose (e.g., English) of documents was used
- Not all model interpreters need be human

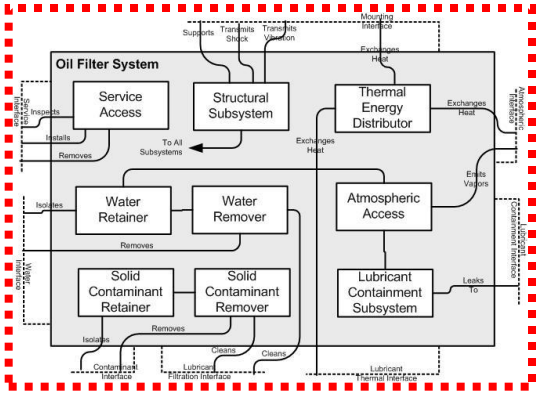


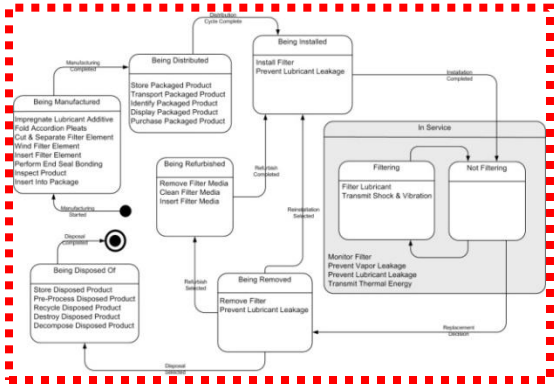
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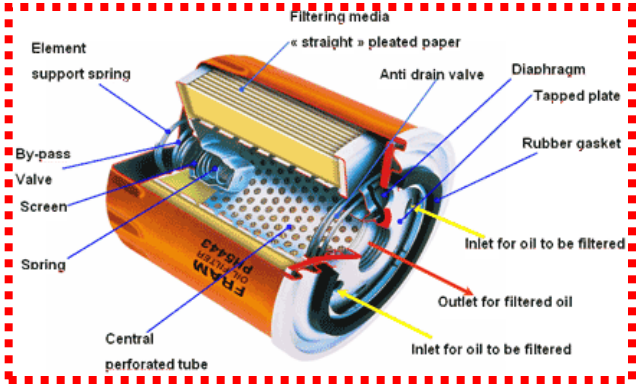
Assumed MBSE background we'll need

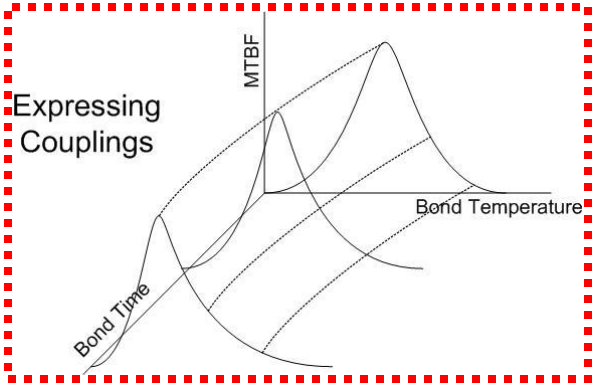
There is a growing practice and literature on Model-Based Systems Engineering.







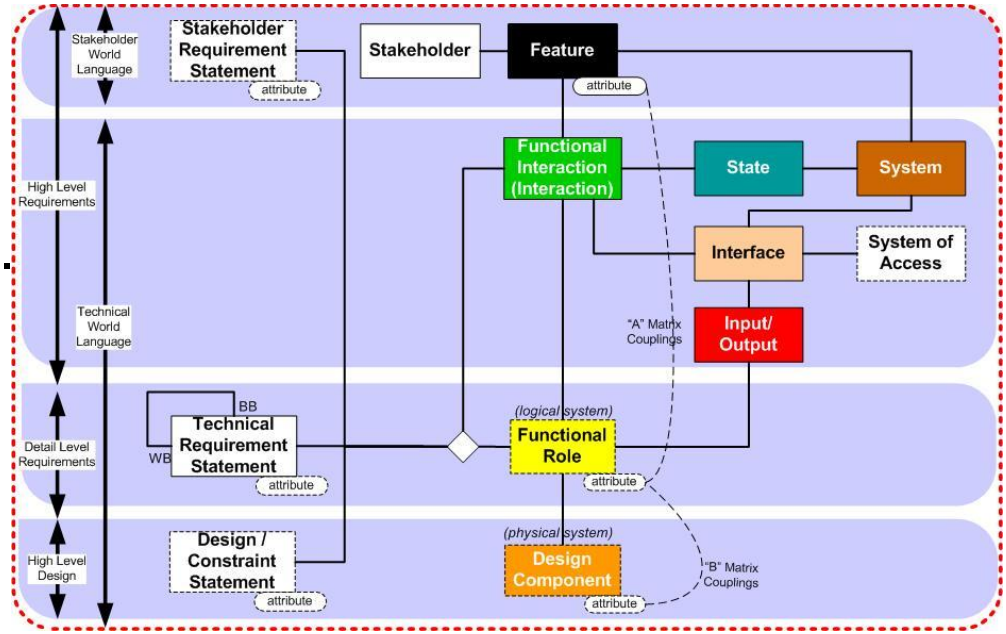




The Systematica approach to MBSE

- Uses models ("blueprints") instead of prose, to specify requirements and design of complex systems (product systems, manufacturing systems, operations processes, the engineering process, etc.).
- Increases understanding while lowering costs.
- Establishes a common language and data model for all systems engineering , across people, tools, information systems—for leadership as well as technologists.
- Expresses model-based formal industry standard (e.g., ISA) descriptions of systems.
- Uses Systematica Metamodel to express underlying concepts.

Simple summary of detailed Systematica Metamodel.

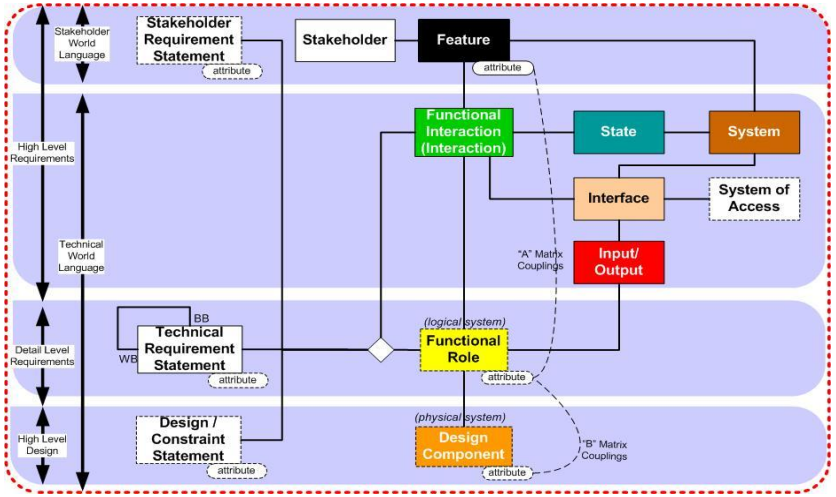


Model-based systems engineering (MBSE)

What does Systematica mean by “Metamodel”?

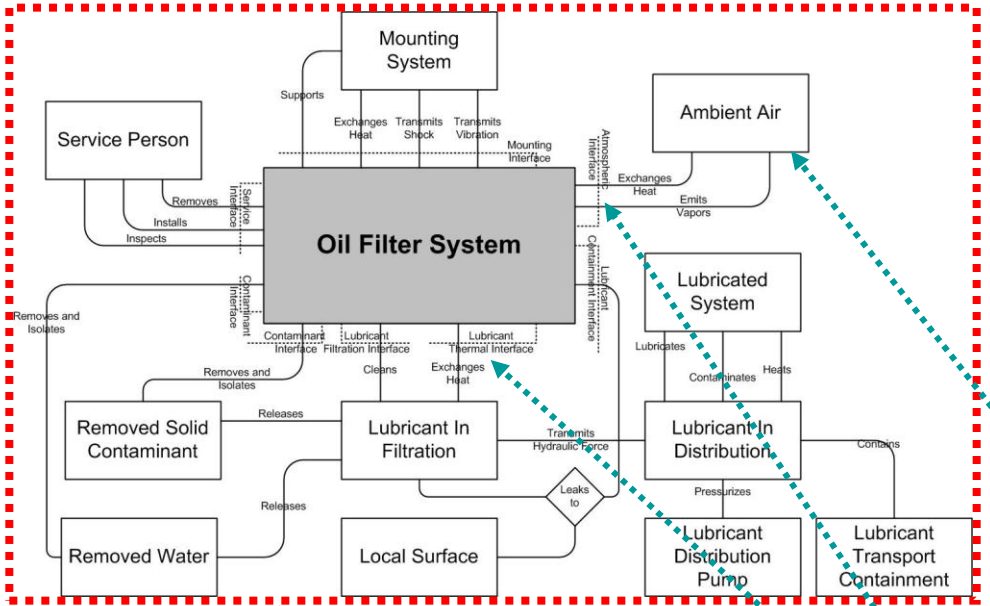
- The framework in which all models are described
- *The minimum set of ideas necessary to express all concepts of system requirements and design, independent of technology*
- The overall model to which any system model must conform
- Constrains community to a common framework, across technologies and functions
- Within this framework, we create an Enterprise or Industry Language for Shared Patterns, to consistently express system requirements, designs, validations and verifications, FMEAs, etc.
- Incorporating industry, enterprise, governmental standards as needed

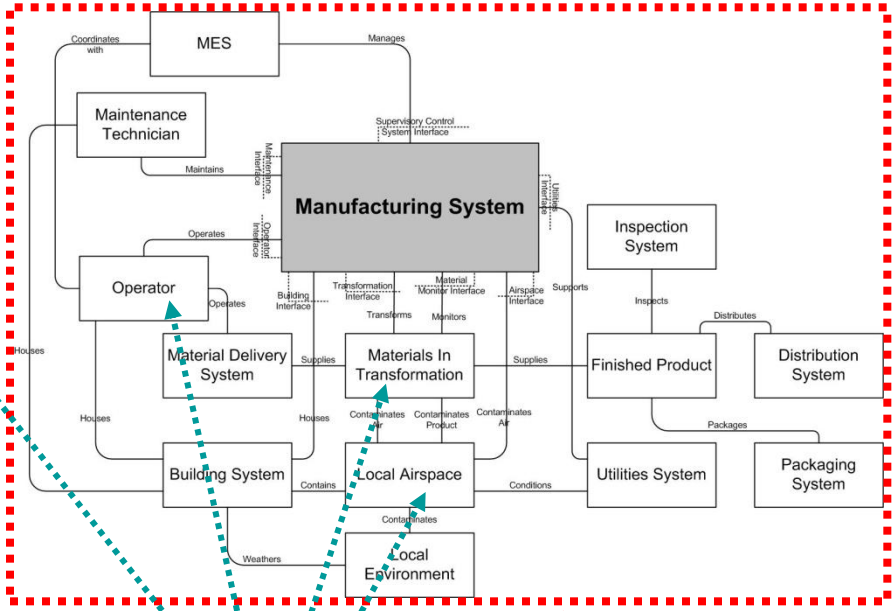
Simple summary of detailed Systematica



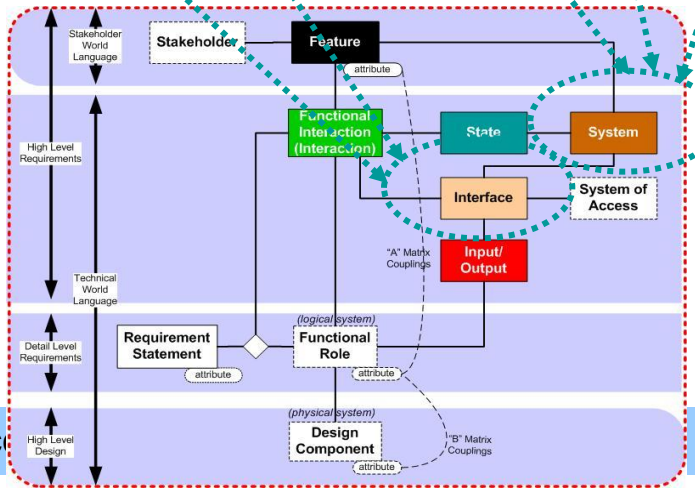
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Models can describe Manufacturing Systems as well as Manufactured Products.





Product Application Domain Model

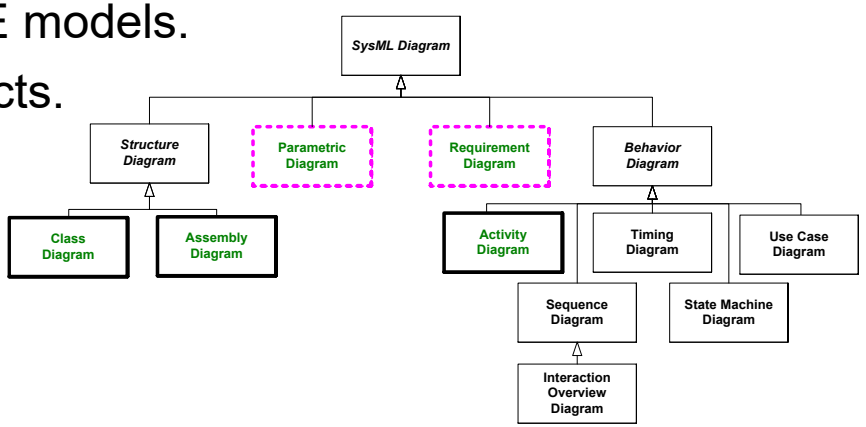


Manufacturing Domain Model

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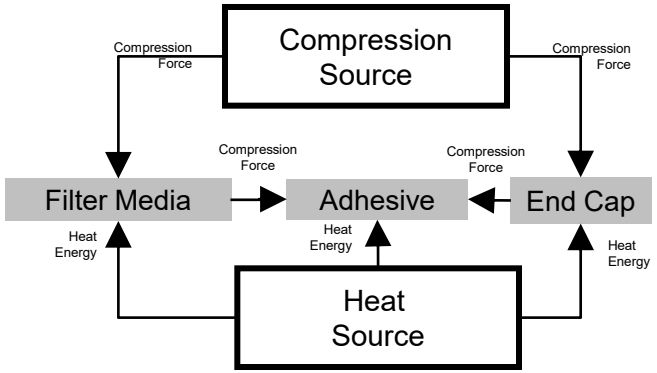
Assumed MBSE background we'll need

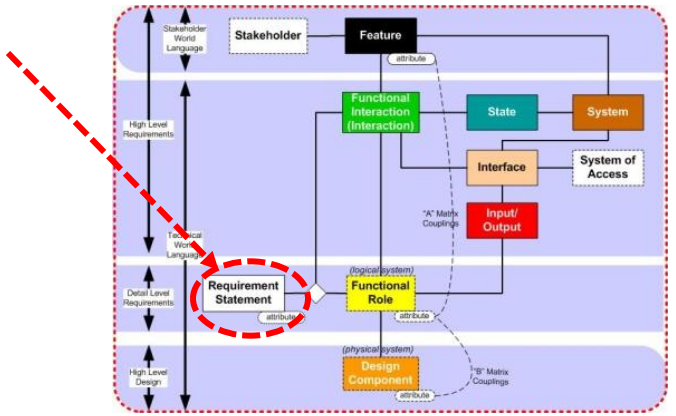
- Model-based methods supplement the use of natural language prose in traditional engineering documents with the use of "models" which are explicit data structures (typically relational tables and formal diagrams).
- The structure of these models can be exploited to create analyses and checks that would be much more difficult and subjective to perform using purely prose-based methods.
- When applied well, they can also more effectively convey shared meaning to human readers.
- We will focus here on how Manufacturing Transformations can be more deeply integrated as a part of such MBSE models.
- See the attached example for other aspects.



Modeling transformation behavior

- This Metamodel re-positions prose functional “Requirements Statements”:
  - These textual statements become a formal part of the model.
  - All functional requirements are modeled as external interaction behaviors.
  - They become input-output relationships describing external system “black box” behavior during Interactions with external actors—a “prose transfer function”:
    - *“The Manufacturing System shall deliver to the Materials In Process a Compression Force of [Min Bond Force] for a period of [Min Bond Time]”.*
    - *“The Manufacturing System shall deliver to the Materials in Process Heat Energy sufficient to maintain a bond temperature of [Min Bond Temperature] for a period of [Min Bond Time].”*

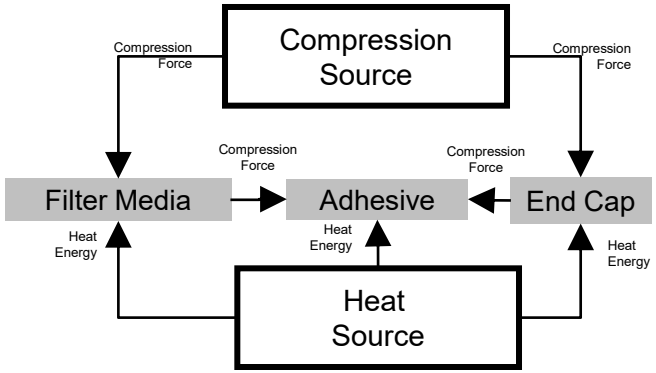


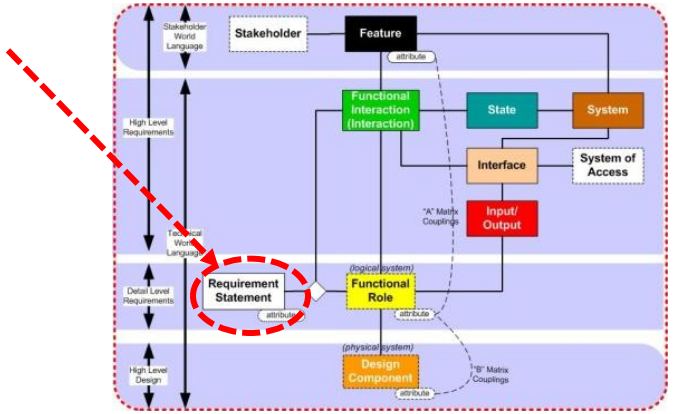


- Further described in (Schindel 2005a).

It works for the Materials in Process, as well as the Manufacturing System

- In the same way, in the same model we can describe the required behavior of the Materials in Process:
  - *"The Adhesive, Filter Media, and End Cap shall bond upon input of a Compression Force of [Min Bond Force] for a period of [Min Bond Time], accompanied by input of Heat Energy sufficient to maintain a bond temperature of [Min Bond Temperature] for a period of [Min Bond Time]."*
  - *"The Oil Filter shall operate in service at Lubricant Pressure of [Max Lubricant Pressure] with bond or other structural failure rates less than [Max Structural Failure Rate] over an in-service life of [Min Service Life]."*



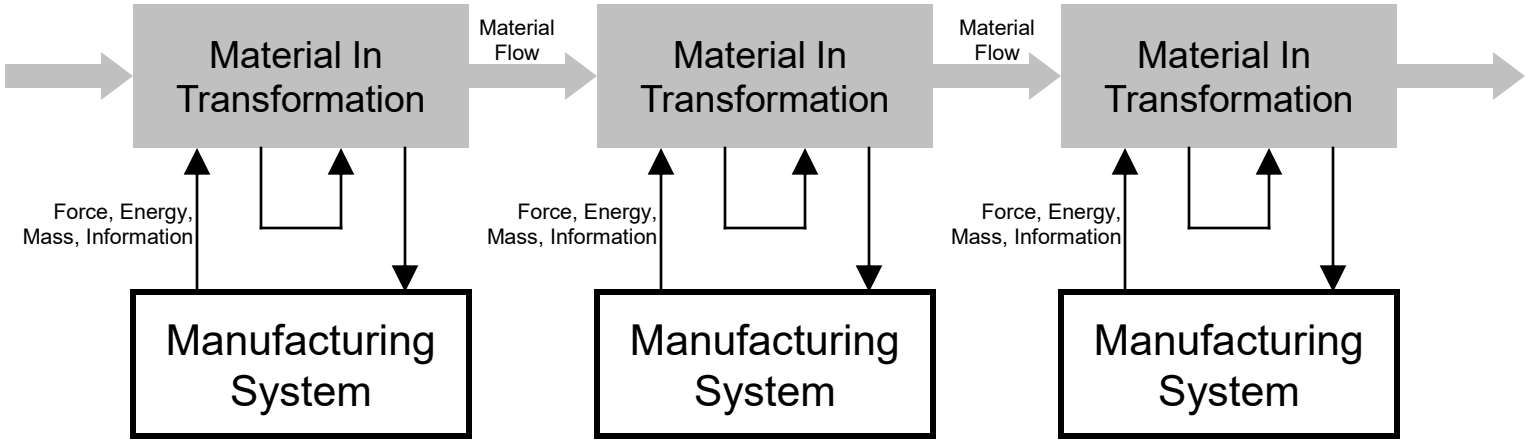


- Further described in (Schindel 2005a).

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Applying the concepts to manufacturing processes

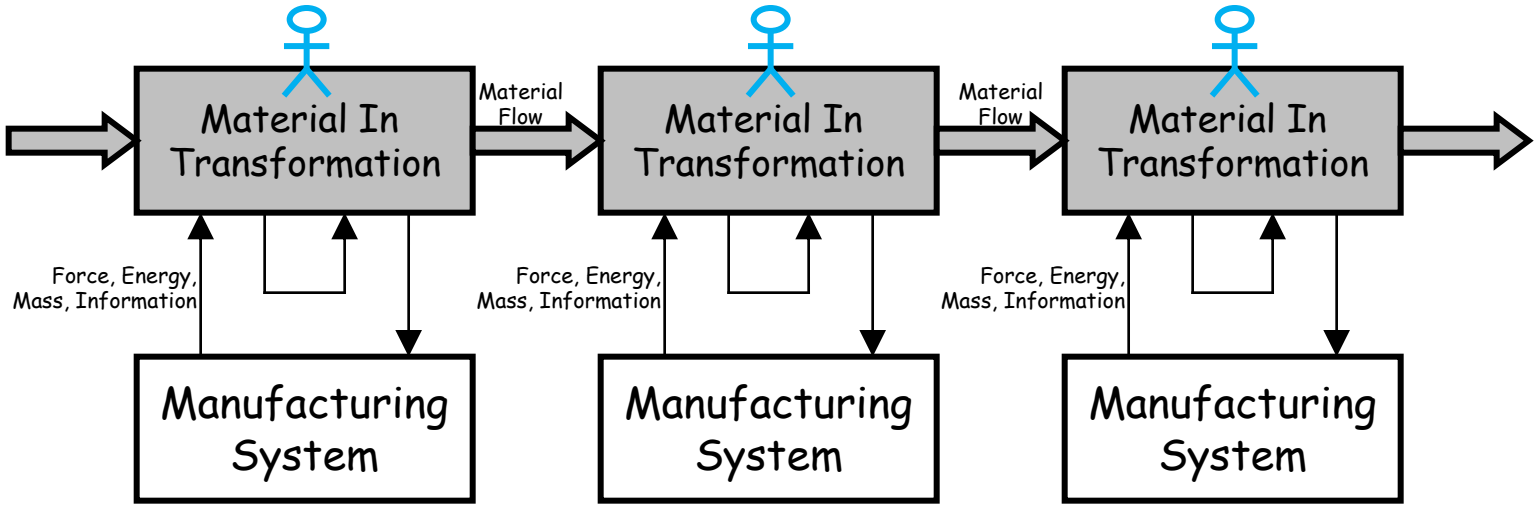
- For some process engineering specialists, material scientists, or other disciplines, an understanding of the behavior of the material during transformations is essential:
  - bending, forming, structural deformations, cutting, milling, extruding, compression
  - chemical, biochemical, electrochemical reactions, distillation, fermentation, etc.
  - heating, cooling, bonding, welding, fastening, mixing, blending
  - other transformations
- These specialists think about the “Material In Transformation”:
  - how the material behaves during each of a series of sequential unit operation transformations;
  - During each transformation, the Material will exchange energy, force, mass, or information with the Manufacturing System, as well as with itself--



Process: What the Material "Sees"

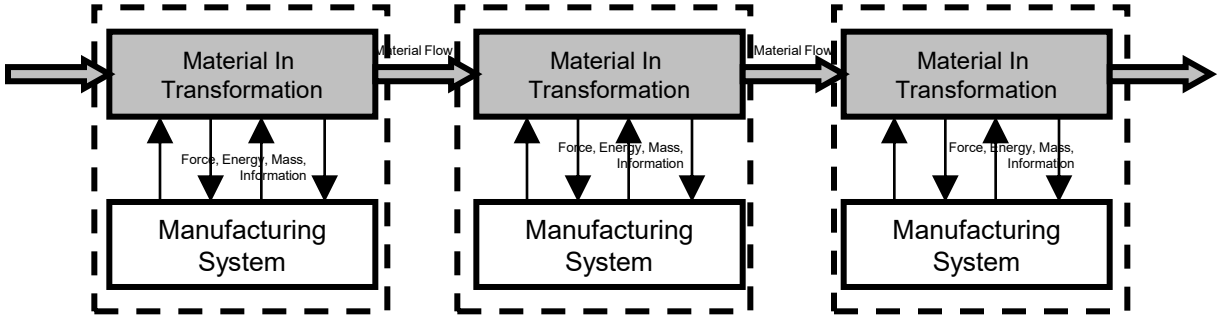


- Imagine that you could "ride through the process with the material".
- Imagine that you could "see what the material sees" (forces, temperatures, etc.).
- This is the "process view" of the process engineer, materials scientist, chemist, metallurgist, or other process-related specialist:

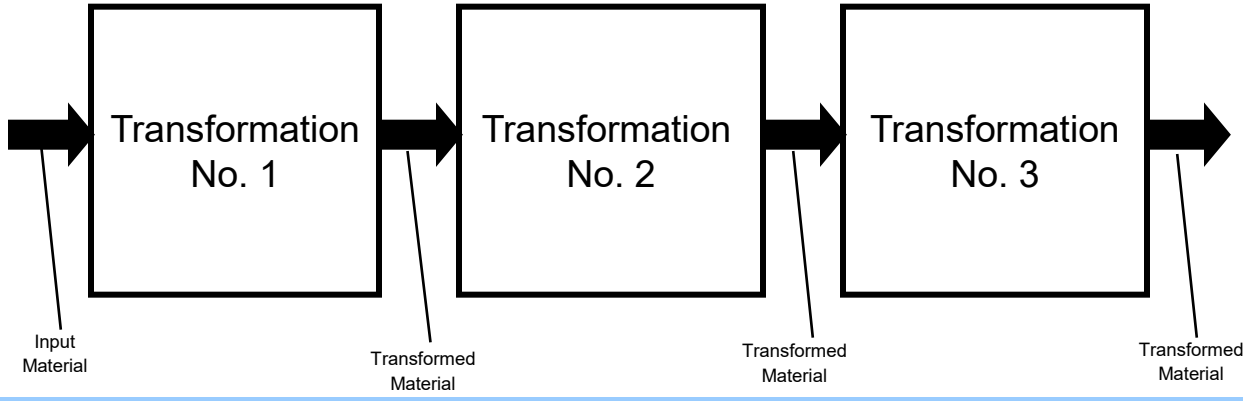


Less detailed PFD views

- Others people's jobs don't need that much detail, so they think of the transformations as "black boxes"; so that . . . .



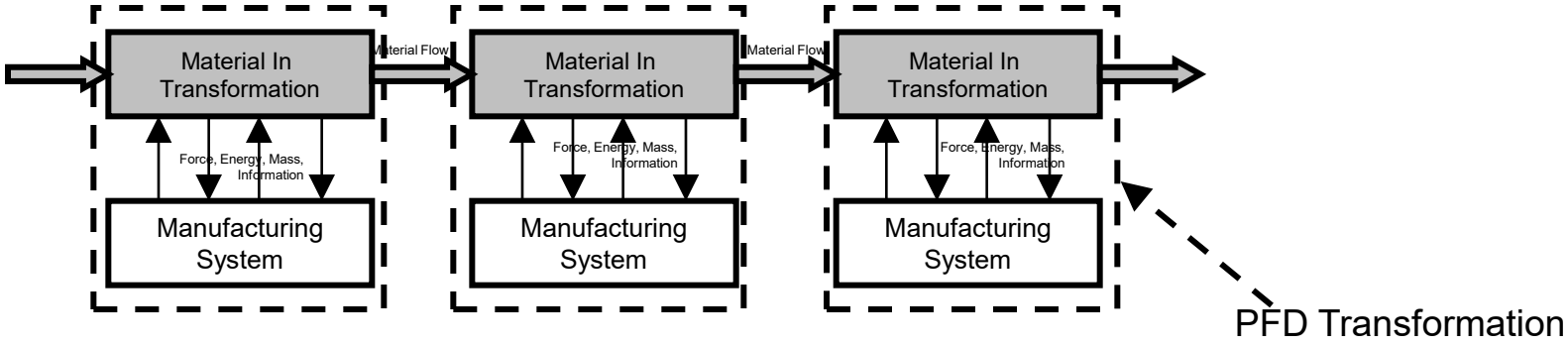
becomes a Process Flow Diagram (PFD):



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Material In Transformation can be modeled as "logically outside" the equipment's transformation role

- Difference between these two representations:
  - the Material In Transformation is "logically outside" the Manufacturing System, but . . .
  - that Material In Transformation is "logically inside" the PFD Transformations:



- After all, the Material In Transformation is not a part of the BOM of the Manufacturing System!
- The advantage of this approach is that it allows us to use the MBSE technique that *all the functional requirements on the manufacturing system are found at the points of input-output boundary crossings of that system*

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"Registered Process" As Requirements

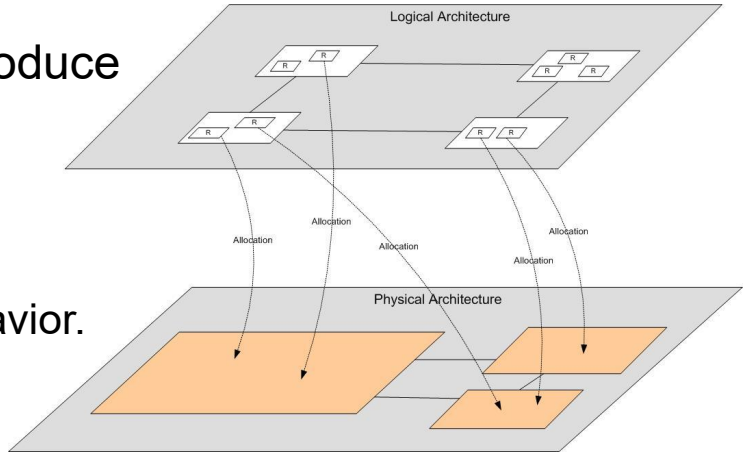
- Many manufacturing "processes" have a kind of managed existence separate from their specific implementation with equipment:
  - When a PFD describes a process before there is equipment design;
  - When a "registered process" has been approved by a regulator, and a factory is constructed to implement that specific process;
  - When a low-volume process has come out of a laboratory to a pilot production line, but not yet been scaled up to production volume.

- This reflects the idea that the requirements of a manufacturing system are something more than producing the end outputs from the initial inputs—it is also expected to embody a specific targeted manufacturing process.

- This is why we model the "Materials In Process" as an external actor interacting with the equipment.

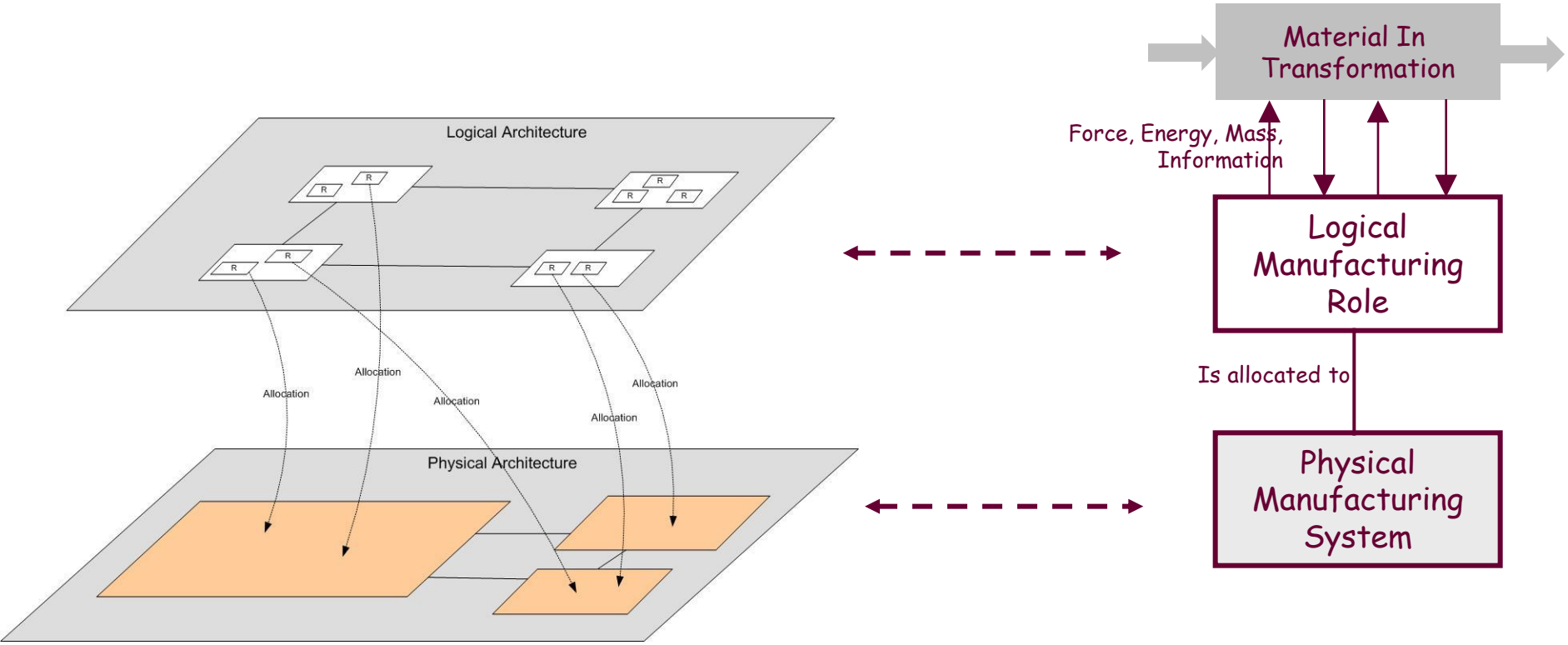
Logical Systems vs. Physical Systems

- MBSE expresses what the Manufacturing System contributes to the process, using Logical Systems:
  - Logical systems are defined by their required externally visible behavior, as seen by the other interacting actors, without regard to the physical design used to accomplish that behavior.
- Logical System Roles:
  - represent transformation or other behavior of the manufacturing system, without regard to its design.
  - Certain Logical Manufacturing Roles must produce (or consume) certain forces, energy, or information, exchanged with the Material In Transformation.
- Physical Manufacturing Systems:
  - Are defined by their physical identity, not their behavior.
  - Logical behaviors are then allocated to physical equipment.
- Logical Roles are allocated to Physical Systems



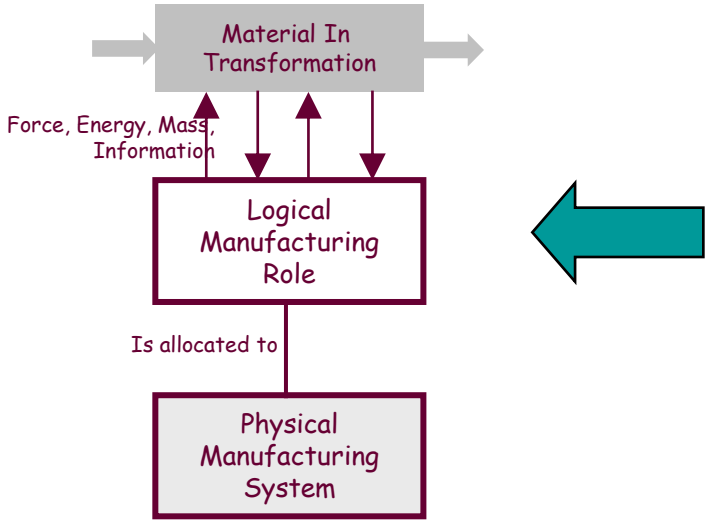
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Logical Systems vs. Physical Systems



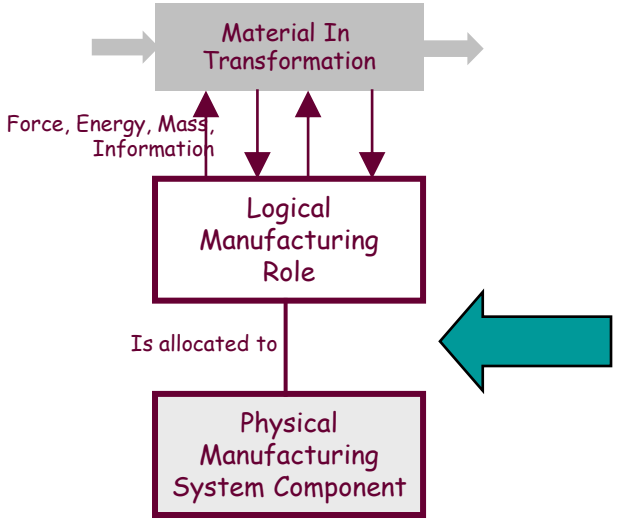
Manufacturing system requirements

- The input-output relationships (relationships between input-output Forces, Energies, Masses, Information that are exchanged with the Material In Transformation) of the Logical Manufacturing Roles turn out to express the requirements allocated to the Manufacturing System to accomplish the transformation:



Manufacturing equipment design

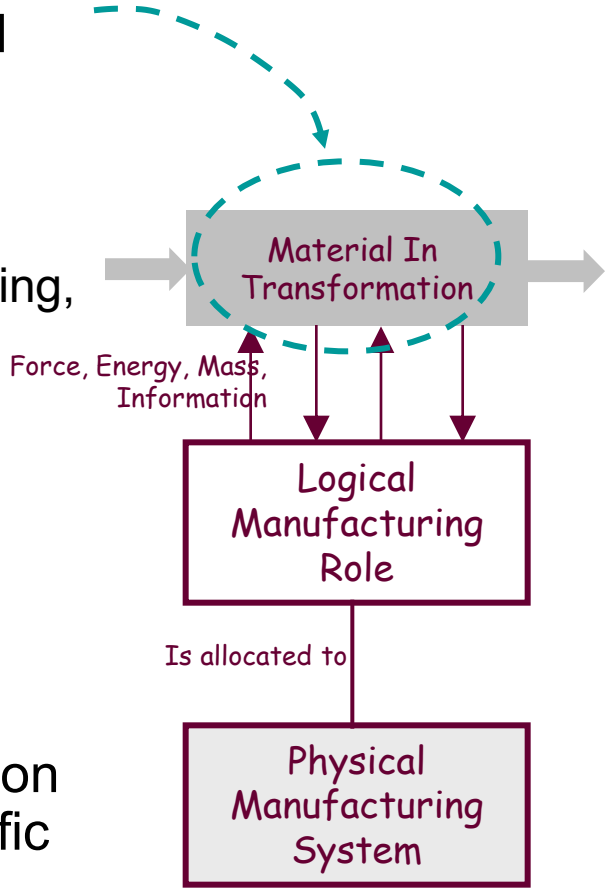
- The allocation of logical manufacturing roles to physical equipment components describes the high level design of the manufacturing system:



- This begins the embedding of process requirements into an integrated framework of system requirements.

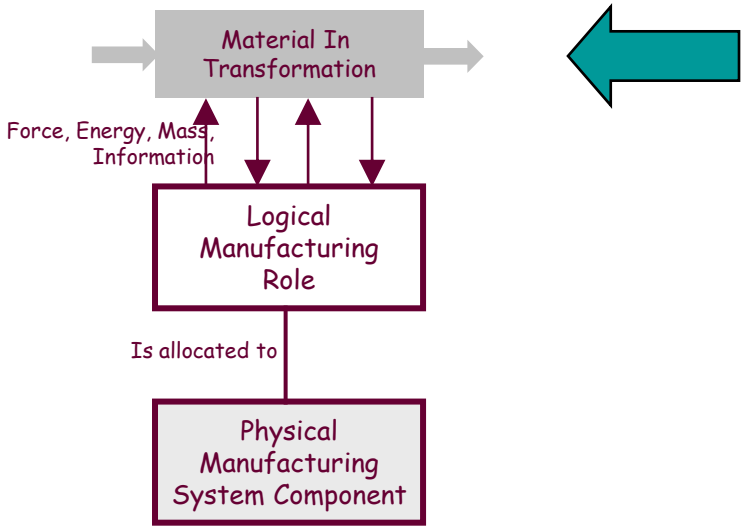
Materials roles

- For materials scientists, chemists, metallurgists, and other specialists in materials . . .
- These specialists seek out materials that have properties desirable for transformations:
  - bending, forming, structural deformations, cutting, milling, extruding, compression
  - chemical, biochemical, electrochemical reactions, distillation, fermentation, etc.
  - heating, cooling
  - bonding, welding, fastening
  - mixing, blending
  - other transformations
- The logical transformation model facilitates description of those properties, somewhat independent of specific materials:
  - Encourages understanding of materials requirements and opens thinking to new materials solutions.

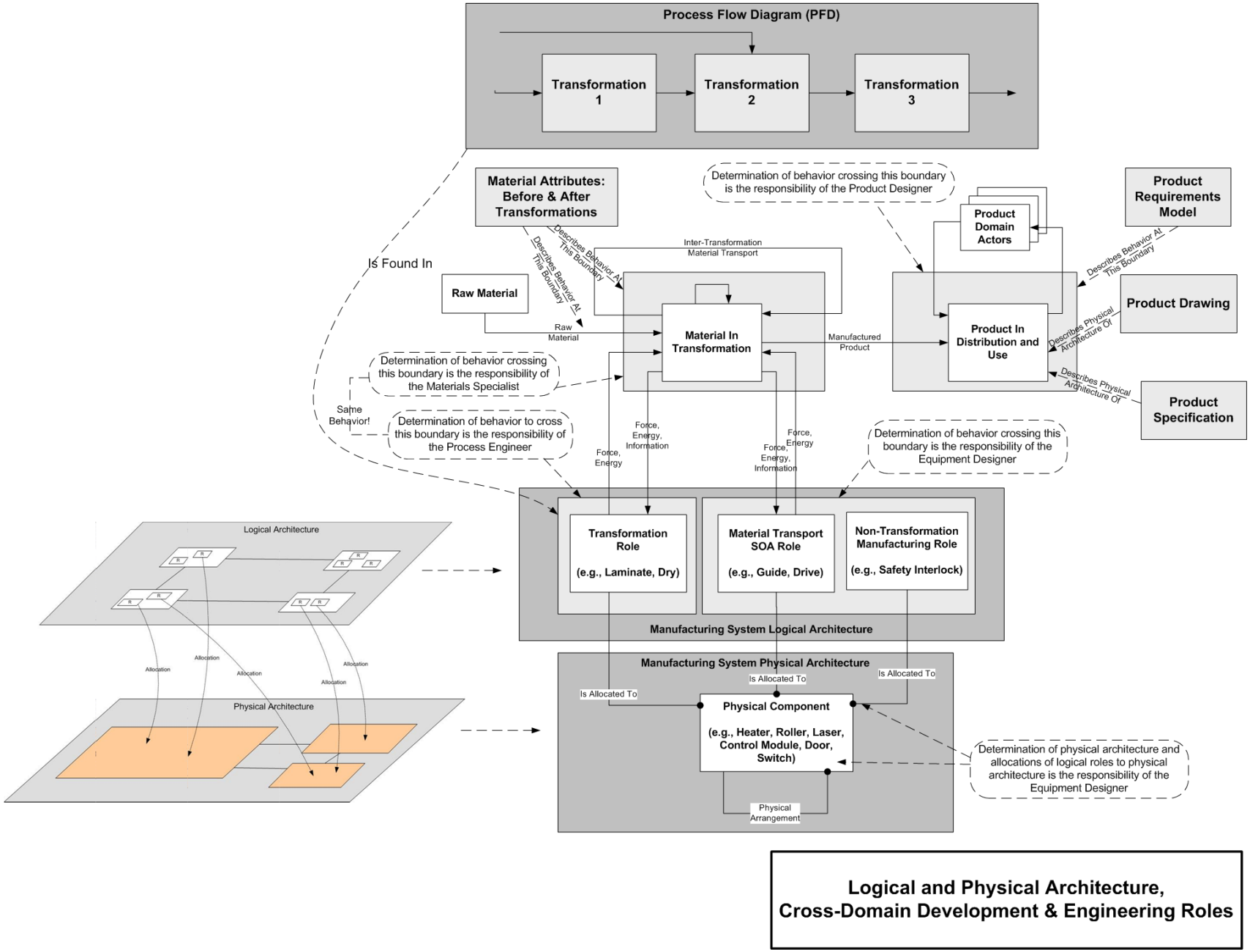


Materials roles

- Just like the equipment, logical roles are allocated to the Materials In Transformation, which they must satisfy in order for the transformation (or transport) to succeed:



- This means that we can create an integrated model that couples the roles of interest to the process engineer and equipment design with those of interest to the materials specialist . . . .



Logical and Physical Architecture, Cross-Domain Development & Engineering Roles

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Conclusions

Model-Based Systems Engineering helps . . .

1. Integrate science-based understanding of processes, materials, and transformations into the life cycle engineering of manufacturing systems.
2. Improve integration of Process Engineering with other engineering disciplines.
3. Improve manufacturing process IP capture—particularly using PBSE.
4. Improve teams' and individuals' abilities to "think outside the box".
5. Speed discovery of new product and process implications for equipment design.
6. Improve understanding of newer references and standards for describing manufacturing processes that use the language of "models" (e.g., ISA S.88).
7. Improve the ability to perform long-range planning and portfolio management of manufacturing technologies, along with related product science and technologies.

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Additional information

- Non-transformation manufacturing roles
- Manufacturing patterns, parameterized recipes
- Unit operations vs. higher level systems
- Portfolio management
- An extended example

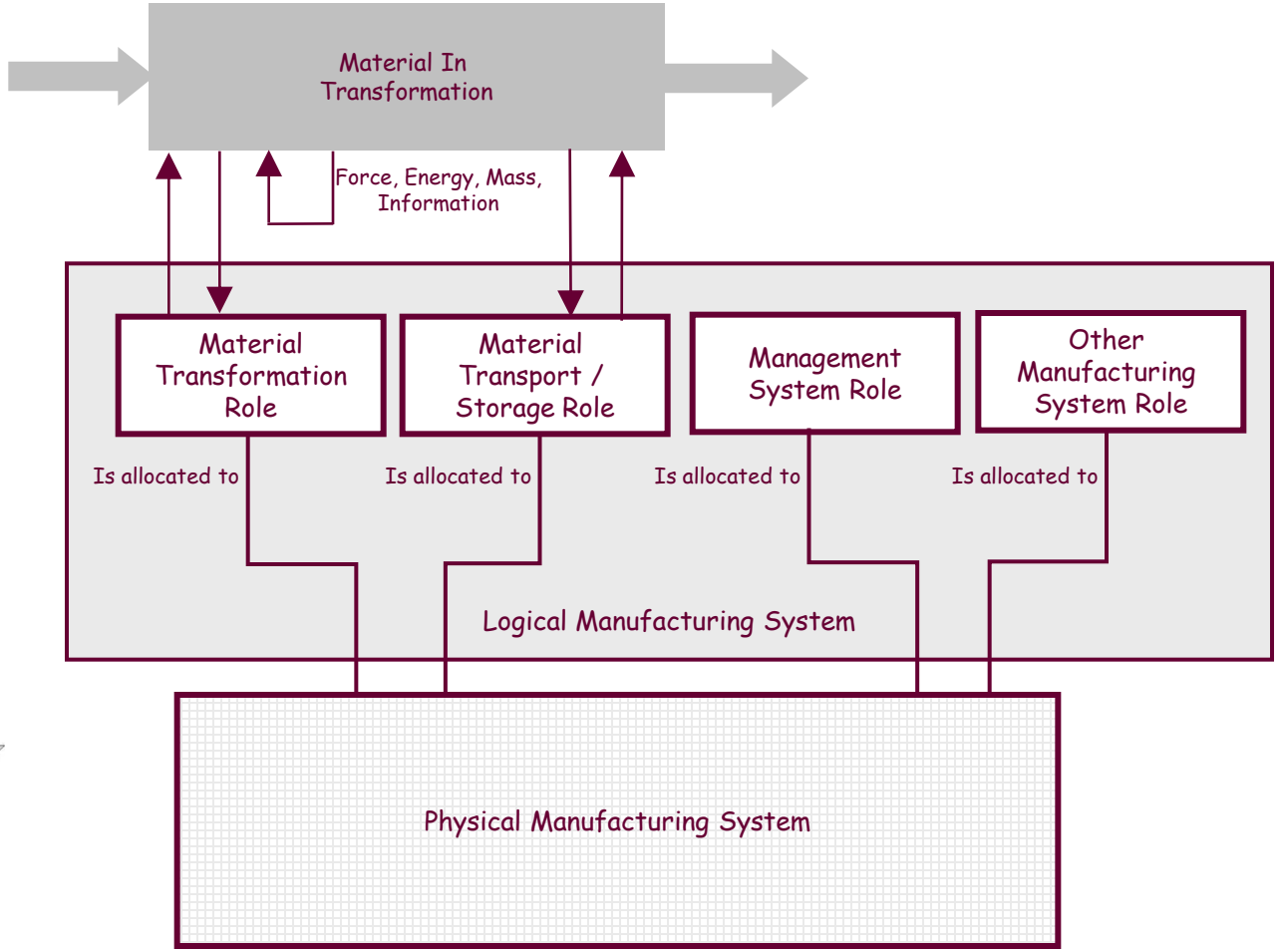
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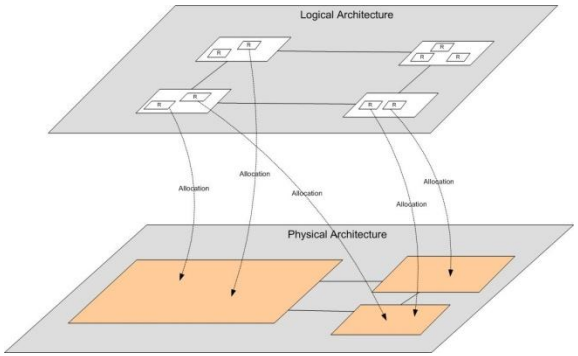
Non-transformation manufacturing roles

- There are additional logical roles that the Manufacturing System must perform, beyond physical transformations.
- For example:
  - Transport and storage roles;
  - Material systems of access (interface) roles;
  - Infrastructure roles (utilities, etc.);
  - Management: Operations, maintenance, configuration, security, accounting roles

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Non-transformation roles





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Transport and storage roles

- Requirements on the manufacturing system for:
  - Transport (movement of material in process)
    - Liquid transport
    - Web transport
    - Powder, solid materials, gaseous transport
    - Logistics considerations, carriers, space, etc.
  - Storage
    - Roles typically filled by tanks, warehouses, shelves, etc.

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Material Systems of Access (SOA) Roles

- A System Of Access is part of an Interface Model—the system that enables physical interaction between two other systems.
- SOAs are important “glue” for practical engineering as well as scientific understanding of system interactions.
- Two SOA classes important to Process Engineering models:
  - Transformation Systems of Access--
    - Example: the logical roles played during material transformations, by heated tank jackets (heat transfer) or bubbling gas through liquids (maximize contact area), etc.
  - Transport Systems of Access—
    - Example: the logical roles played during material transport, by slurry pumps, conveyer belts, augers, rolling bins, etc.
- Separating SOAs in the model improves the ability of the underlying transformation and transport processes to be modeled independent of technology.

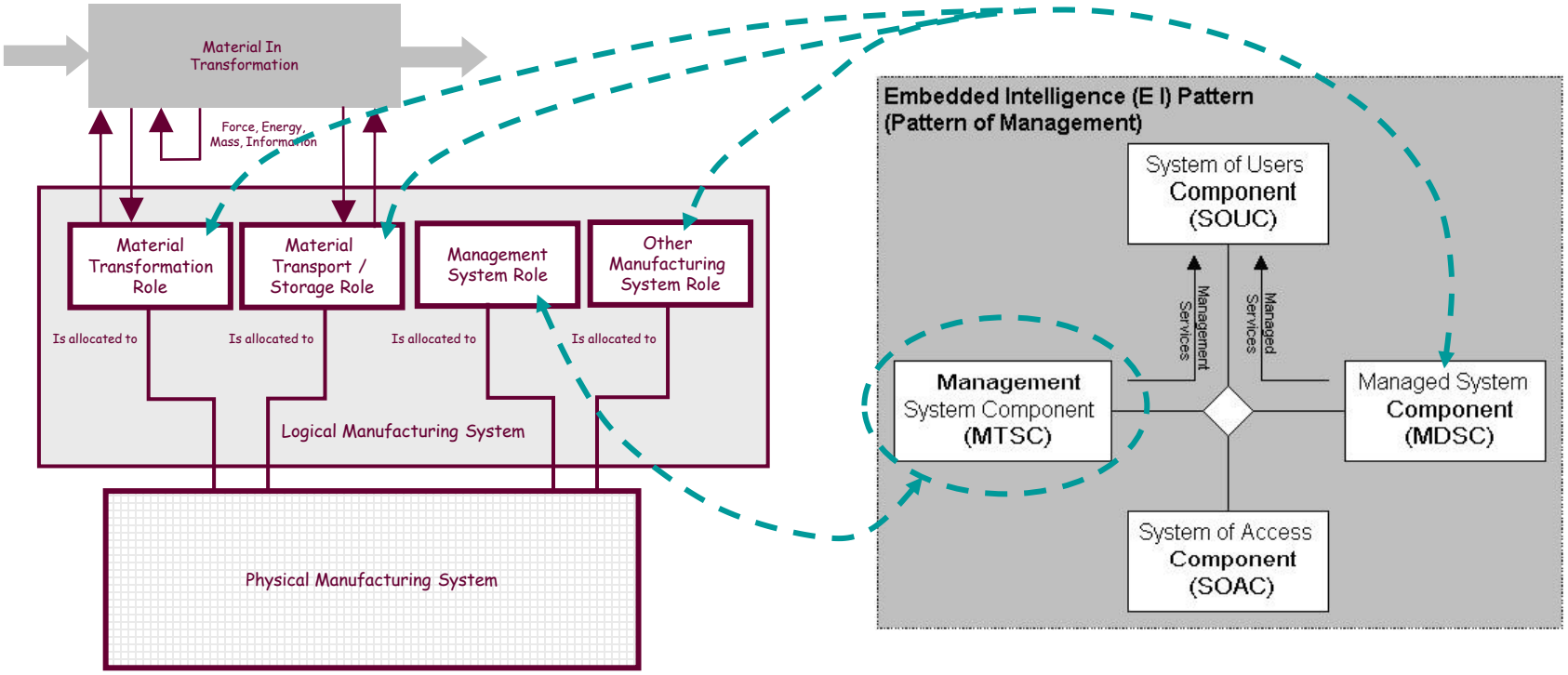
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Infrastructure (utilities, infrastructure, etc.) roles

- Regular utilities (electrical & pneumatic power, heating & cooling media, etc.)
- HVAC
- Clean or specialized utilities
- Consumables treated as utilities
- Waste disposal, treatment, co-generation, or recovery streams
- Plant space, structural resources
- Site resources

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Management roles: Operations, maintenance, configuration, security, accounting



- Electronic controls and automation are “management system roles” that are part of the model.
- These roles are also played by humans (operators, etc.).
- They are usually organized into hierarchical controls patterns:
- For more on this, consult the Systematica materials on Embedded Intelligence (EI) Pattern of Intelligence-Based Systems Engineering (IBSE).

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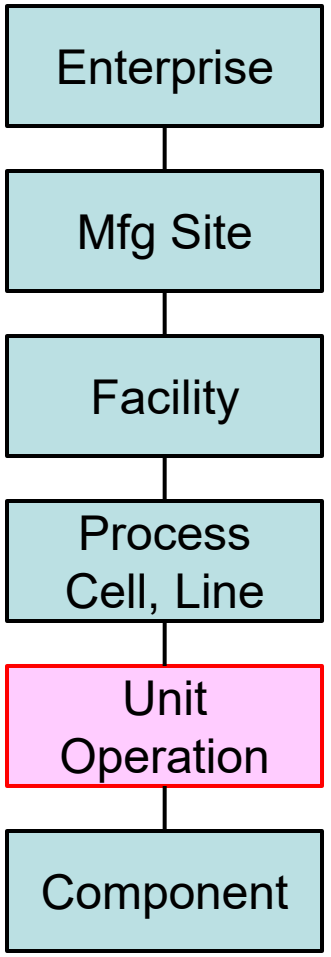
Manufacturing patterns, parameterized recipes

- MBSE “models” describe both requirements and design, for both equipment and materials;
- PBSE “patterns” are re-usable Models, requiring less effort to use than creating Models from scratch;
- Patterns can be configured for different needs and uses:
  - One reason to configure a general pattern is to describe a site specific system (e.g., a manufacturing system installed at a site).
    - A single configured system of this type might still be capable of carrying out many different recipes.
    - This type of configuration is “configuration at design time”.
  - Another reason to configure a pattern is to express a specific recipe:
    - This has the effect of configuring a site specific system for a single recipe, and is a “configuration at run time”
  - For more on this, see the Pattern Configuration Process, ISA S.88, etc.

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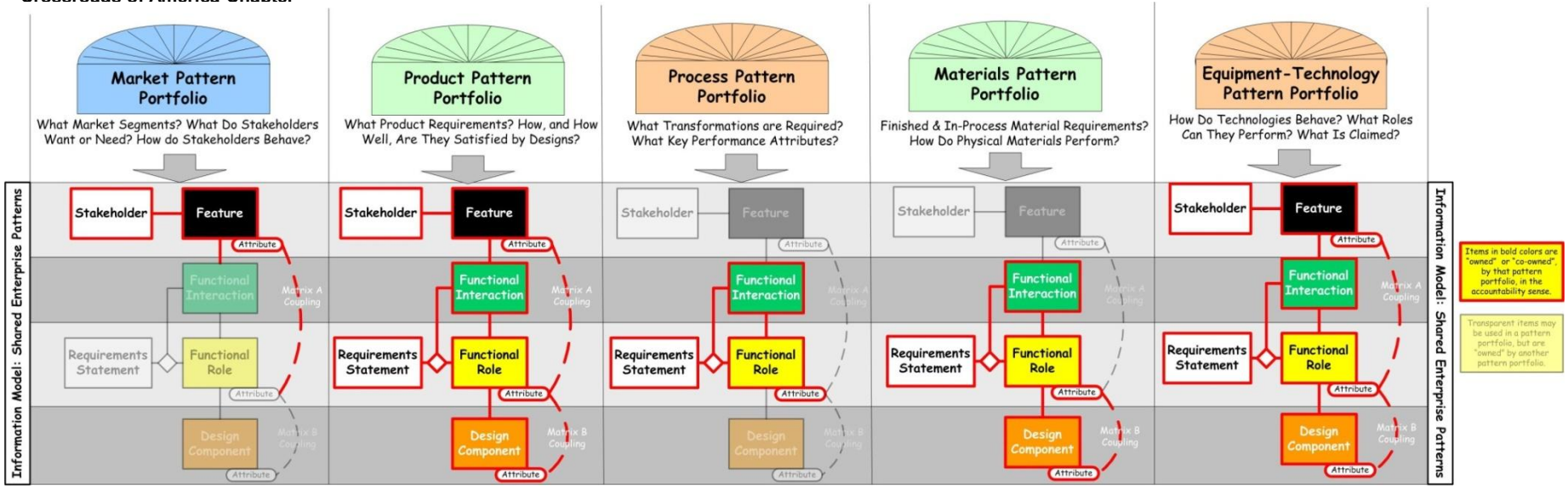
Unit ops vs. higher level aggregations

- The “materials in transformation” approach to modeling particularly applies to the Unit Operation level, where the transformation occurs;
- There are many other requirements not about transformations, and other hierarchy levels, as well;
- This is all very typical SE hierarchy of decomposable requirements;
- Frequently addressed by multiple disciplines or specialties, and integrated together by SE;
- As usual, it also means that there are attributes (parameters) that are characteristics of the different levels—some are lower level process attributes, but couple to higher level product Quality, Capacity, Yield, Cost, or other critical attributes;
- MBSE attribute coupling models help to make the relationships between these attributes more evident—typically these couplings are characterized by DOE studies, first principles, process characterization, and other sources.



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Portfolio Management, Using Patterns, From Long Range Plans to Current Development



- Extracts / subsets of MBSE models also make it possible to represent and manage "Portfolios" (families) of related:
  - Technologies—of Manufacturing, Materials, and Products
  - Customer or Application Market Segments
  - Product Families, Product Lines
  - Master Plans—for production facilities, capital allocations
- The coordination of these across large enterprises is frequently difficult, and can be greatly facilitated by these explicit portfolio models.

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An extended example

- Insertion:
  - Oil Filter Manufacturing & Product Model Extracts