INTEGRATING MATERIALS, PROCESS & PRODUCT PORTFOLIOS: LESSONS FROM PATTERN-BASED SYSTEMS ENGINEERING

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ABSTRACT

The challenges of integrating efforts of materials scientists, process engineers, product developers, and manufacturing equipment designers are well-known. To support those efforts, large enterprises and industry sectors frequently establish (formal or informal) "portfolios" of material and process technologies and other assets. Such portfolios represent components that may potentially serve in integrated solutions addressing innovation needs. However, formalized portfolios may also be a part of the problem, if they create additional barriers or "silos" within the specialized domains they represent, obscuring insights needed for innovative solutions. This paper examines how "System Patterns" found useful in Pattern-Based Systems Engineering (PBSE) can be used to better understand and address all these challenges, by supporting an improved information framework for the management of separate but collaborative portfolios for technologies, processes, materials, and other assets.

1. INTRODUCTION

1.1 What This Paper Is About, and for Whom

This paper summarizes the use of Pattern-Based Systems Engineering (PBSE) methodology to address the two sets of challenges. The first is the technical integration and management of the development and operation of a complex manufacturing system, including the related materials, processes, and manufacturing equipment, in coordination with development of the related manufactured product. A second, related challenge is finding an effective approach to the creation, management, and use of "portfolios" of materials, process technologies, other manufacturing assets, and products, in an overall enterprise library of re-usable assets to improve the life cycle learning capabilities of the enterprise.

This paper is suitable for leadership and technical staff in materials science, process engineering, equipment design, information technology, product line management, and systems engineering. It is intended to increase awareness of new approaches to improving innovation performance.

1.2 Challenges of Manufacturing Process Systems

1.2.1 Traditional Process Engineering Perspectives

Process engineers are trained to visualize manufacturing as a series of transformation of materials. This is frequently represented using Process Flow Diagrams (PFDs) and supporting descriptions [1].

In Figure 1, the material flowing out of each block is different in comparison to the material flowing in—it is transformed chemically, structurally, thermodynamically, visually, in information content, etc.:

Figure 1. Process Flow Diagram (PFD)

Figure 2 illustrates a simple manufacturing example--the fabrication of an oil filter cartridge, through a series of unit operations:

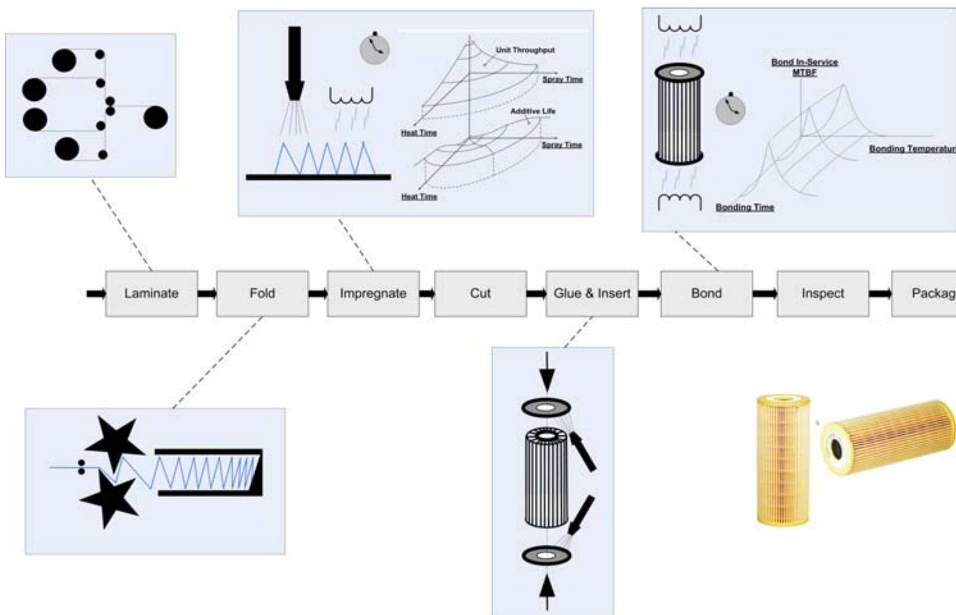


Figure 2. Example Manufacturing Process: Fabricating an Oil Filter Cartridge

By omitting manufacturing equipment-specific design from these descriptions, the traditional 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. Refer to Figure 3.

Figure 3. The PFD Represents Process Without Equipment Design

Since it describes the required transformations the manufacturing system must perform, such a PFD description is a form of requirements on the manufacturing system.

1.2.2 The Complexification of Manufacturing Systems, Materials, and Products

Advanced manufacturing systems continue to grow more complex. Semiconductor fabrication has been joined by biotech pharmaceutical manufacturing, embodying living processes. Automotive production integrates subsystems resembling avionics-loaded aerospace vehicles of previous eras. Medical devices must be fabricated to sustain human life as robust implants or mission-critical diagnostic and therapeutic systems. Aerospace manufacturing processes transform advanced materials for operational environments and performance beyond what would have been conceivable a generation earlier. The growing complexity of the production systems that perform these manufacturing miracles equals or exceeds the growing complexity of the systems they produce—and the engineering of these advanced manufacturing systems faces a broad range of systemic challenges.

1.2.3 Related Challenges

Process Engineering and PFDs provide powerful tools for conceptualizing manufacturing processes. However, the fact they use a perspective or language separate from design of equipment eventually requires that the enterprise bridge a gap when integrating process engineering into the larger equipment engineering context. Even though PFDs contribute to the equipment requirements, they are only a limited part of the total set of requirements on the equipment—and may even embody inherent conflicts with other requirements.

This raises issues of how to integrate the "process view" (as in a PFD) into the larger engineering process for manufacturing systems, materials, and products:

1. How do we integrate the language, perspective, expertise, and efforts of manufacturing process engineers, materials scientists, automation specialists, equipment designers, and other specialists in the planning and engineering of the manufacturing system?
2. How do we best represent <u>manufacturing</u> systems to facilitate their delivery-time qualification and acceptance and their post-delivery operation, maintenance, evolution, and future technology transfer to other owners or operators?
3. How do manufacturing <u>process</u> requirements fit into the overall manufacturing system requirements, which have larger scope?
4. How do <u>materials</u> requirements integrate into this manufacturing picture?
5. What is the relationship of physical equipment design to these requirements?
6. How can process requirements for new or modified products be incorporated early enough in the equipment design cycle?
7. How are manufacturing system requirements that are not transformations of material related to those that are?
8. How can we conceive new manufacturing solutions without being mentally trapped in assuming constraints of past designs? How do we take advantage of historical lessons?
9. How can candidate manufacturing designs, design changes, and design risks be objectively and transparently evaluated in light of process engineering needs?
10. How can increasingly complex manufacturing systems best be supported by subsequent life cycle engineering?
11. How can portfolios of potential manufacturing technologies be managed alongside

portfolios of future products and materials?

12. How do we assure ourselves and our stakeholders that a manufacturing system design and the related operating and maintenance plans will produce a stable flow of product, meeting the requirements of the product end user, in the presence of normal variation in materials, human behavior, and environmental conditions?

1.3 Supporting Manufacturing's Return to Science

Scientific discovery and its application through engineering and technology are the foundation of many products. However, the systems for manufacture of those products represent a separate (although coupled) space. The manufacturing space may become dominated by an operations culture that emphasizes production pragmatism, intuition, experience, and judgment honed over a long period of relatively stable manufacturing paradigms, "tweaked" from time to time as necessary. Although some manufacturing domains are driven by science from the time of their origin (semiconductor fabrication comes to mind), other manufacturing processes may turn to scientific analysis only when production problems demand a deeper understanding of the related phenomena. The demands to produce more complex or unfamiliar products, the pressure for higher productivity manufacturing, or the need to rapidly transfer, reconfigure, or change manufacturing processes are often wake-up calls driving enterprises back to the related scientific questions [2], [3].

1.4 Quality by Design (QbD)

An key distinction is scientific analysis to understand what went wrong in an existing production system design versus as the original basis of that design. This difference is not only important to productivity of the innovation process, but is essential in some critical products to assure that the product consumer is not placed at undue risk. For example, in the case of manufacturing systems for medical devices and pharmaceuticals, the FDA has encouraged case (2) as "Quality by Design" [4], [5], [6], [7], [8], [9].

2. BACKGROUND: MODEL-BASED SYSTEMS ENGINEERING (MBSE)

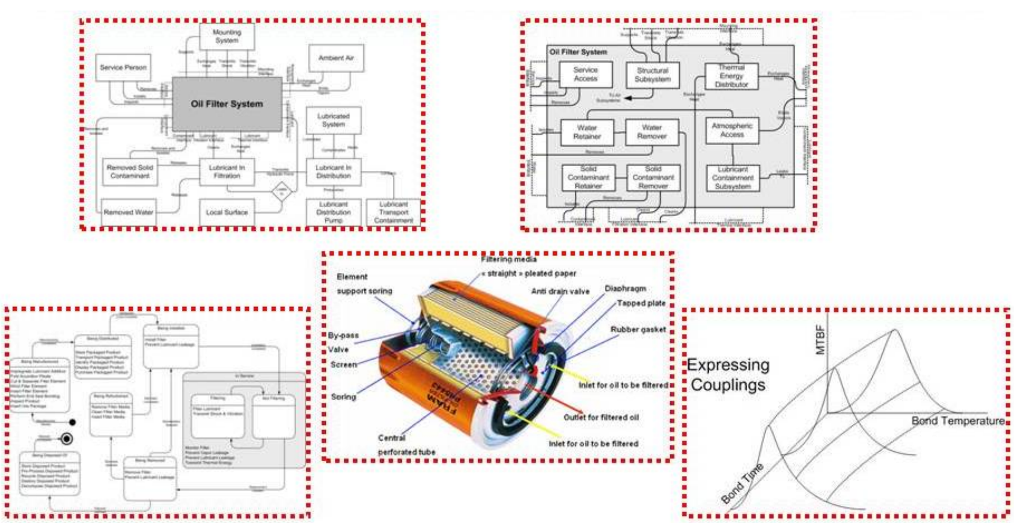


Figure 4. Models Increasingly Appear In Product Engineering

2.1 The Rise of Model-Based Methods.

The story of Model-Based Systems Engineering (MBSE—see Figure 4) is extensively described in other references [10], [11], [12].

We summarize here only some key elements needed to describe the more focused subject of this paper. Most model-based engineering descriptions include and cite these benefits:

1. A more explicit representation of requirements, design, or other information than might otherwise have remained implicit or unstated in earlier approaches.
2. More effective processes of discovery of system requirements.
3. Faster convergence on a common understanding across teams.
4. Greater leverage from model-supporting IT tools, including in some cases integration with specialty areas such as simulations or software construction.

Model-based methods have arisen in a number of disciplines in recent decades. The software community and the systems engineering community have worked to improve the effectiveness of model-based methods through the development of modeling language standards, such as UML® (for software engineering) and SysML® (for systems engineering). The approach we will describe here can readily be applied in any number of modeling languages, as it is about fundamental systems ideas that any systems modeling language should be capable of supporting.

2.2 The Model-Based Approach Used Here.

The rise of model-based methods in engineering in general, and in systems engineering in particular, is transforming our ability to represent the systems we design. The approach described by this paper makes use of model-based methods to extend what was available in PFD-focused approaches, and to technically integrate more scientific knowledge in the resulting description.

A Process Flow Diagram with its associated parameters is itself a type of model. However, even supplementary information typically associated with a PFD presents less than the potential integration of information possible to meet the objective of a science-based representation of a manufacturing unit transformation. [13] As in a traditional PFD, we will still avoid entangling our process requirements model in an assumed equipment design, but will do so while adding the scientifically-based information fundamental to the phenomena basic to the required unit operation.

We will make use of modeling concepts drawn from the summary S*Metamodel of Figure 5. The S* Metamodel re-positions prose (as well as mathematical) functional “requirements statements”, which 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 exhibited during interactions with external actors. They become an extension of the idea of “transfer function”, describing (prose) input-output relationships [11]. In addition, this same model data structure expresses mathematical relationships, when available, and this provides a basis for the embedding of scientific laws and their parameters (from first principles to DOE characterizations). The integration of attribute (parameter) coupling relationships is inherent to this metamodel. See also [14] for a discussion of “how much model” is needed.

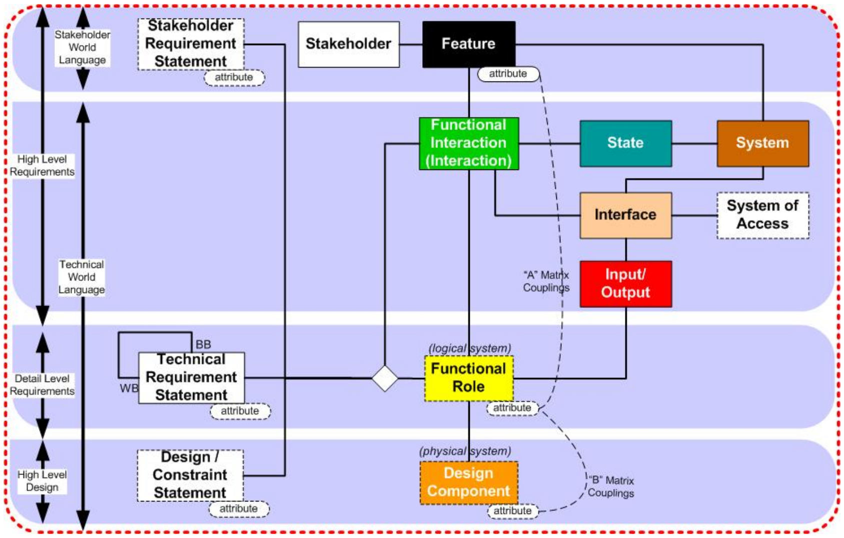


Figure 5. Summary of S* Metamodel

3. RESULTS I: MANUFACTURING SYSTEM INSIGHTS FROM MODEL-BASED METHODS

3.1 The Idea In a Nutshell.

A basic idea exploited by this approach is the extension of the process PFD model, when describing unit operations, to explicitly model the interactions between the Material In Transformation and the Manufacturing System, explicating their logical roles during interaction. This can be done in such a way as to omit the design of the Manufacturing System, while providing an improved basis for describing the required process as seen by the Materials. The result remains PFD-compatible, as its model views can easily and automatically be transformed to PFD views when needed. There are a number of positive implications of this approach, including clearer connection to the science of the process and more explicit integration with the rest of the requirements.

3.2 What Does the Language of Science Talk <u>About</u>?

3.2.1 Interactions: The Representation Framework of Science.

What would a "science-based approach" look like in the development of production systems? A typical answer is to suggest that scientific first principles (the description of related phenomena in terms of laws of nature, perhaps calibrated by DOE data) should appear prominently in the description of the underlying processes of production. This brings us back to the Unit Operations (individual transformations) that have historically been the subject of PFD models. Is it sufficient to surround these diagrams with the equations of the associated physical laws? What is the difference between "looking scientific" and actually practicing science-based development of production systems? Given a legitimately science-based approach, how can we inspect it for unintended gaps or inconsistencies? What would a "gap" in this representation look like?

Since Newton, scientific knowledge of natural phenomena has described behavior, and in particular behavior of interacting entities. Virtually all scientific knowledge is expressed within the framework of representation of physical interactions. Literally everything we know from the physical sciences is about the behavior of interacting components—whether in chemical reactions, electromagnetic, acoustics, mechanics, thermodynamics, or other discipline-specific domains. This science-based interaction framework is not always recognized explicitly in engineering practice, leading to negative impacts. Addressing this is an appropriate goal for Systems Engineers. In this paper, we return to this foundation as the basis for improving the representation of unit transformations—carrying a science-based view into engineering practice.

This perspective is also informative for systems engineers and system scientists, for it reminds us of one possible emphasis in the definition of what we mean by "system" in the natural world: A system is a collection of interacting components. (See Figure 6.) By "interacting" we mean that one component can impact the "state" of another component (through the interaction). We visualize the interaction as the exchange of energy, force, or mass flows, between interacting components. Through the combined behavior of the whole emerging during these interactions, the holistic idea that there is a system arises:

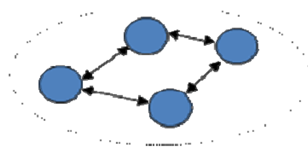


Figure 6. A System Is A Set of Interacting Components

3.2.2 Interaction-Based Representation of Unit Operations

Figure 6 reminds us of the fundamental framework in which substantially all scientific knowledge of natural phenomena is expressed, either explicitly or implicitly—the description of physical interactions. In choosing useful production process models to represent scientific knowledge as explicitly as possible, we should expect that interactions would play a fundamental part in that representation. Figure 7 summarizes the framework we will use for modeling the physical transformations of material during production unit operations (unit ops):

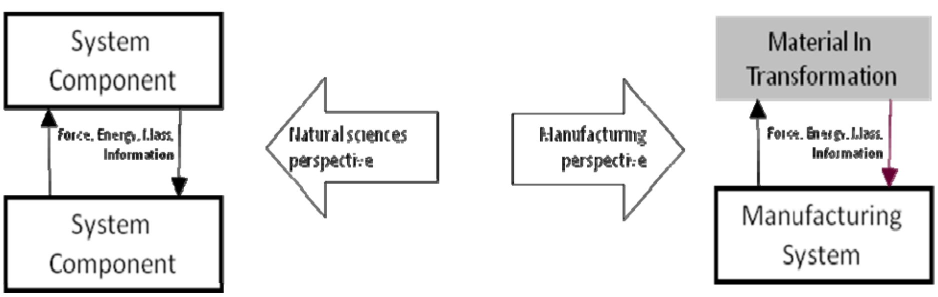


Figure 7. Applying the Scientific Phenomenon Framework to Unit Operations

3.3 An Example Manufacturing Interaction

Consider, for example, the "Bond" unit operation block in the PFD of Figure 3. The intended transformation is to bond the oil filter end cap to the filter media, with resulting bond seal strength sufficient for reliable high-pressure oil filtration in the intended filter product applications. The bonding involves applying an adhesive, compression force, and heat to cure the adhesive. Applying the generic "transformation interaction" framework of Figure 7, we generate the specific model shown on the right side in Figure 8.

Notice how the representation on the right side of Figure 8 is different than the representation of the "Bond" transformation block of the PDF of Figure 3. It is this difference that we will pursue in greater detail below. Note also that this representation nevertheless does not assume any specific design of the Manufacturing System.

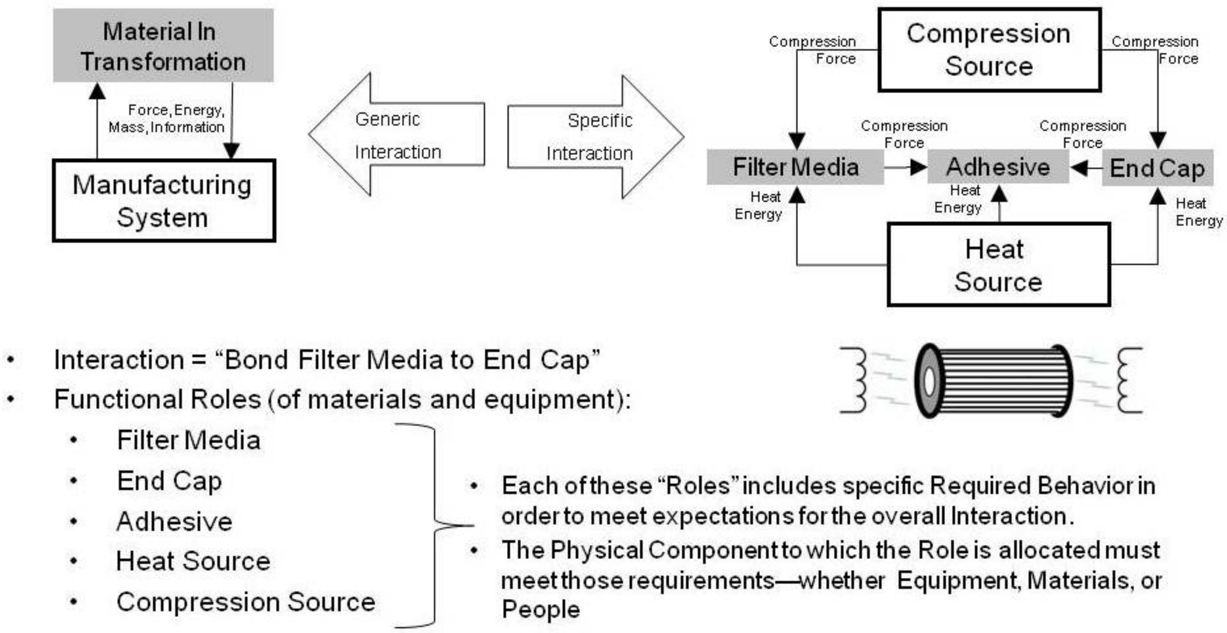
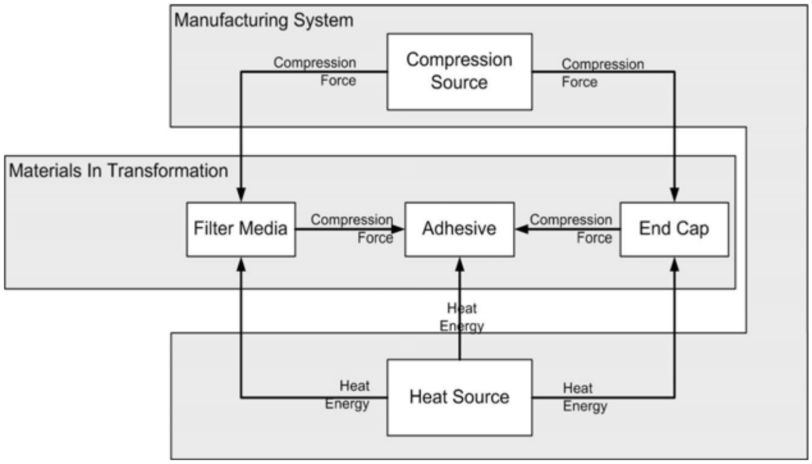


Figure 8. An Example Unit Operation, Viewed As An Interaction

The bonding operation prose requirements statements on the "black box" Manufacturing System express modeled input-output relationships, as shown in Figure 9.

The requirements statements in Figure 9 contain underlines for modeled Input-Outputs in the diagram, and brackets for Attributes (configurable parameters). These can be removed, or retained for additional modeled requirements audit and tool support. Refer to [11]. This is a powerful aspect this MBSE method: *all the functional requirements on a given system are found at the points of input-output external boundary crossings of that system*. This is why we model the Materials In Transformation as an <u>external actor</u> in this approach.



Requirements on Manufacturing System:

"The Manufacturing System shall deliver to the Materials In Transformation a <u>*Compression Force*</u> *of [Min Bond Force] for a period of [Min Bond Time]".*

"The Manufacturing System shall deliver to the Materials in Transformation a <u>*Heat Energy*</u> *no less than [Min Bond Activation Energy] within a period of [Min Bond Time]."*

Figure 9. Modeled Requirements

In the same model, we describe required behavior allocated to the Materials in Transformation:

"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 of [Min Bond Activation Energy] within 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]."

The bracketed attributes within these requirement statements are coupled to each other through coupling relationships that include first principles and materials properties. For some process engineering specialists, material scientists, or other disciplines, an understanding of the behavioral of the material during transformations (such as those in Table 1) is essential:

Table 1: Example Manufacturing Unit Op 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

These specialists think about the Material In Transformation: what happens to the material during the transformation, as shown in Figure 10. They think of the material as it interacts with the Manufacturing System, during exchange of Force, Energy, Mass, or Information:

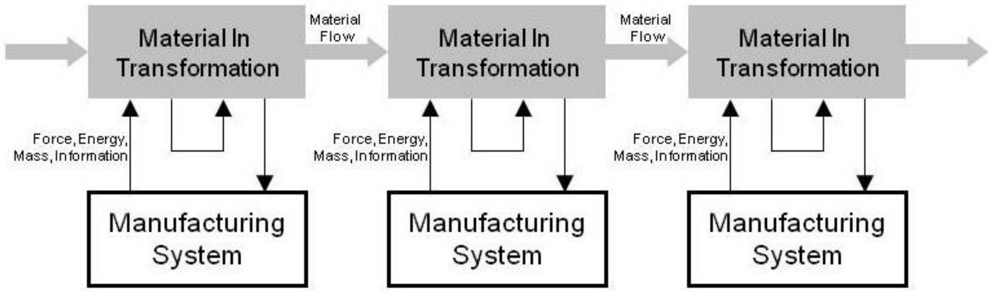


Figure 10. Modeled Material In Transformation

This is a type of process view as "seen" by the materials scientist, chemist, metallurgist, or the material itself. It is the realm in which the scientific laws that govern the unit transformations are to be expressed, harnessed to achieve the engineered objectives of the transformation.

Not everyone needs to see this level of detail. For many, the transformations can be viewed as "black boxes". As shown in Figure 11, this maps the modeled representation back into a traditional PFD model:

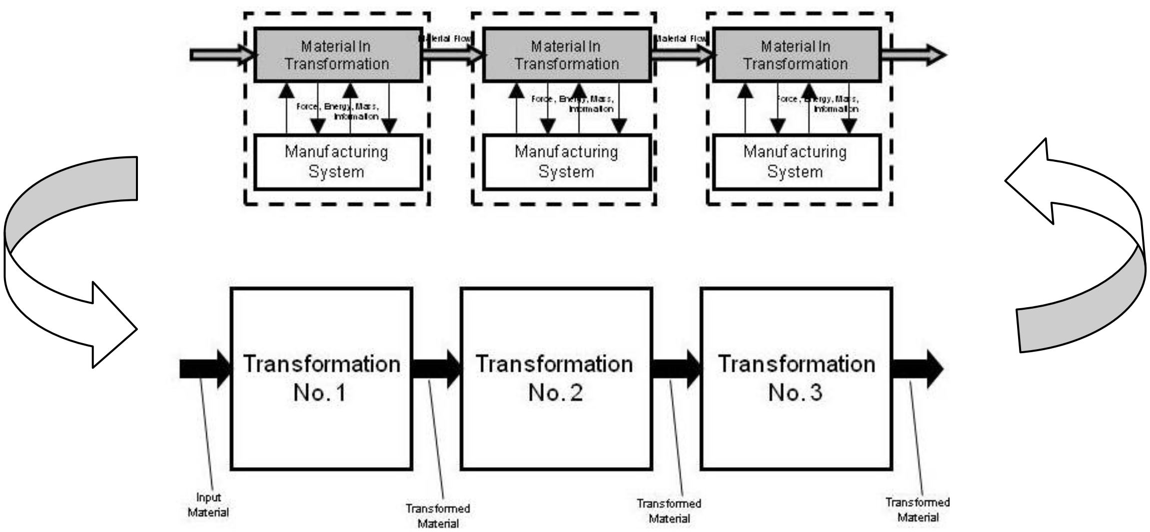


Figure 11. There Is a Mapping from One Representation to the Other

The Material In Transformation is "logically outside" the Manufacturing System, but it is "logically inside" the PFD transformations. After all, the Material In Transformation is not part of the Bill of Material of the Manufacturing System!

3.4 Manufacturing Equipment Requirements and Design

3.4.1 Logical vs. Physical Systems.

Although we are accustomed to referring to a "process" (as in PFD models) as separate from the related equipment design, the approach described here provides an additional way to think about the nature of the separated concept of "process". This arises from the idea of Logical Systems that is a part of the referenced SE methodology.

Logical systems are defined by their externally visible behavior, as seen by the actors with which they interact, without regard to physical design used to accomplish that behavior. By contrast, physical systems are defined by their identity, but not their behavior. In the world of SE, this helps us separate requirements (as behavior) from design (as physical technology implementing that behavior). We can model a logical architecture as the decomposition of behavior into interacting logical roles (behavior components), exchanging force, energy, mass, or information. We can model a physical architecture as the decomposition of the physical system into components and their physical relationships (e.g., attachments, etc.).

The logical roles are then allocated (assigned to) the physical components, representing the allocation of requirements to physical design components (Figure 12).

The roles played by a Manufacturing System and Materials In Transformation, as in the blocks seen in Figure 9, are components of their respective Logical Architectures. These are revealed by decomposing the PFD as shown in Figure 11. 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, mass flows, or information, exchanged with the Material In Transformation—which also has allocated (materials) roles.

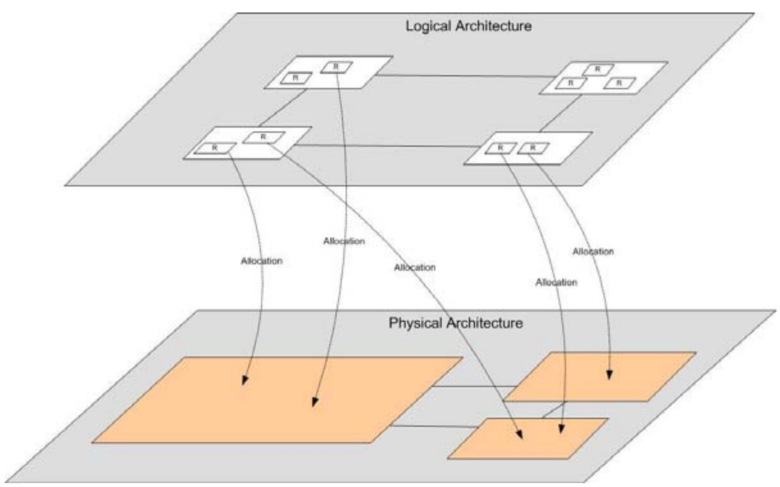


Figure 12. Allocation of Logical Architecture Roles to Physical Architecture Components

3.4.2 Process Requirements On the Manufacturing System.

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 express the requirements allocated to the Manufacturing System to accomplish the transformation. These are expressed by the Logical Manufacturing Role block of Figure 13.

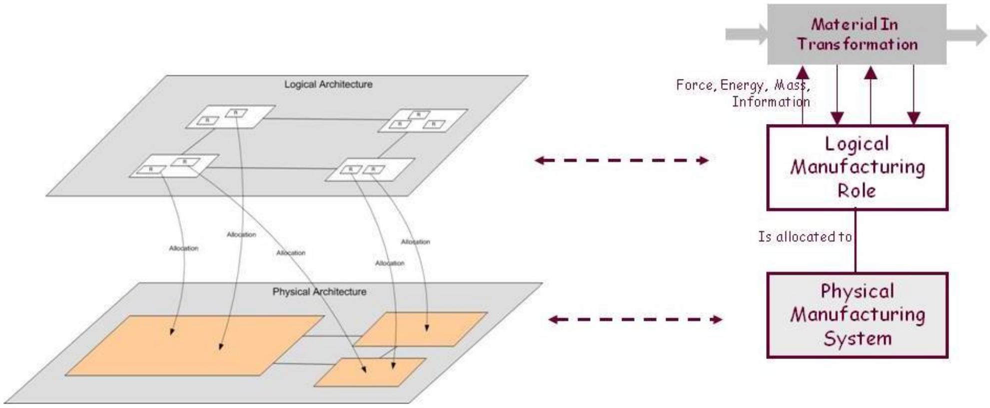


Figure 13. Logical & Physical Architecture for Manufacturing Systems & Materials In Process

3.4.3 Manufacturing Equipment Design.

The allocation of logical manufacturing roles to physical equipment components describes the high level design of the manufacturing system (the Physical Manufacturing System of Figure 13). This begins the embedding of process requirements into an integrated framework of total manufacturing system requirements.

3.5 Materials Roles and Requirements

Materials scientists, chemists, metallurgists, and other specialists in materials seek out materials that have properties desirable for transformations, such as those of the unit ops in Table 1. The logical transformation model facilitates description of those properties, initially independent of specific physical materials. It encourages understanding of materials requirements and opens thinking to new materials solutions.

Just like the equipment, logical roles are allocated to the Materials In Transformation, which they must satisfy in order for the desired transformation (or transport or storage) to succeed. This is illustrated by the material requirements of Section III.2. This means that we can create an integrated model (Figure 14) that couples the roles of interest to the process engineer and equipment design with those of interest to the materials specialist.

3.6 Non-Transformation Role.

The Manufacturing System plays more logical roles than just transformation of materials. These additional roles span the larger scope of all the requirements on the Manufacturing System, such as Materials Transport, Storage, and Infrastructure (e.g, Utilities). The integration further includes operations, maintenance, configuration, security, and accounting roles.

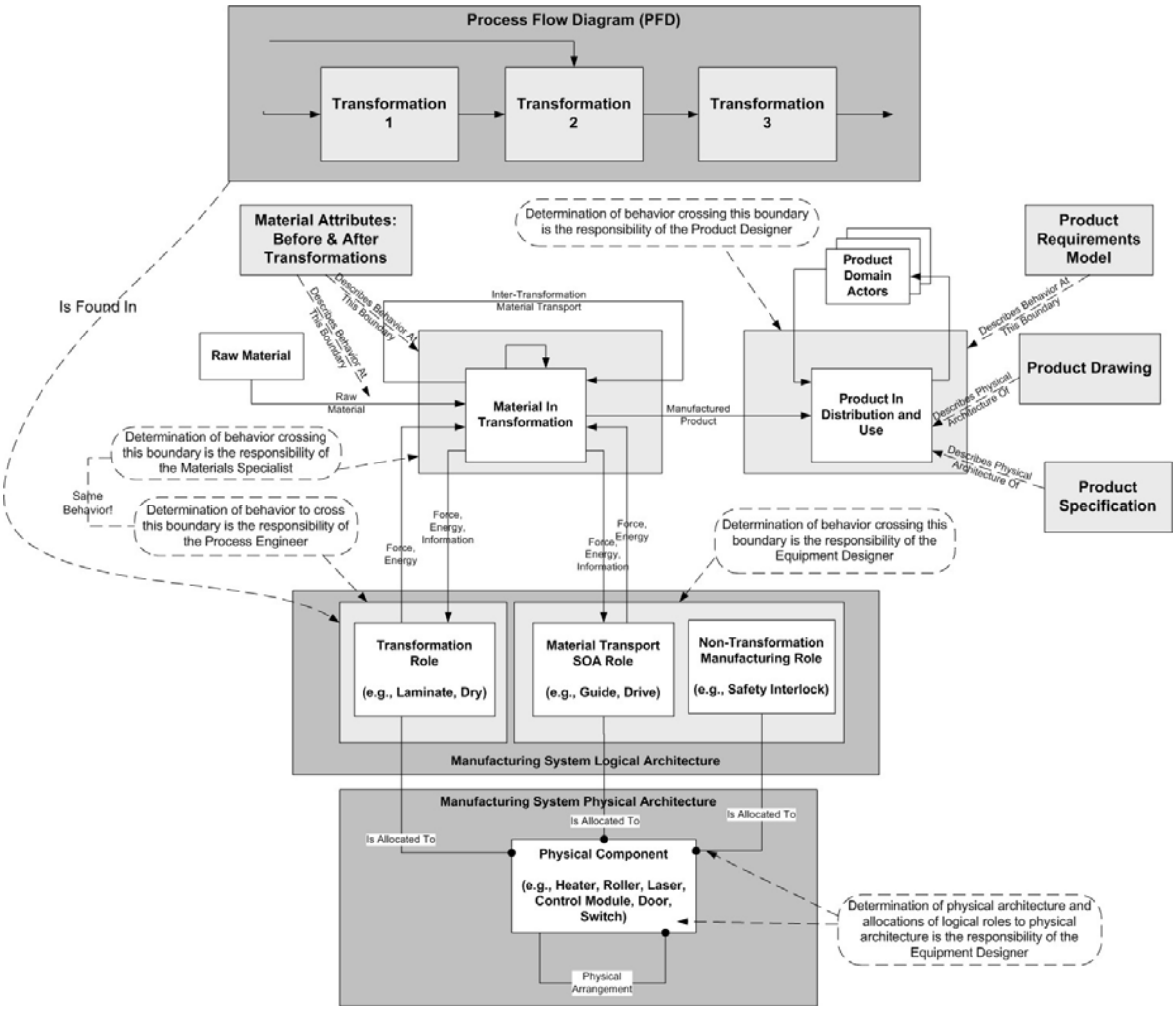


Figure 14. Integrated Model of Roles of Interest to Different Specialists

4. RESULTS II: PATTERNS & PORTFOLIOS: ECONOMIC LEVERAGE IN REAL ENTERPRISES

Patterns can be used to develop better-managed portfolios of Materials, Processes, Equipment, and Products, on an integrated basis across the enterprise, also reducing modeling time. Once the transition has been made to the model-based approach, the stage is set for Pattern-Based Systems Engineering [15], [16], [17]. An S* pattern is a re-usable, configurable S* Model (conforming to the Fig. 5 S* Metamodel), which can be reconfigured for use across different market segments, applications, or customers. Experience with S* Patterns across multiple domains has shown that they can be configured with order-of magnitude (90%) reduction in time to generate requirements by traditional means. As reported in [14], the results have additionally been found to be more complete than traditional approaches.

Such S* Patterns can be thought of as the information equivalent of extending a flexible physical "platform" product or manufacturing system to a parameterized MBSE description of all the information (including key relationships) that describe its requirements, design, trade-offs, risk analysis, and other aspects. Applied in a single domain (say, product or manufacturing equipment), and S* Pattern can already have powerful impacts of reducing effort and variation across innovation projects.

Applied to multiple domains (say, product, materials, manufacturing process and equipment), an even larger value multiplier is possible, because of coordination across enterprise domains. Figure 15 illustrates the recommended “loose-tight” approach. Instead of over-constraining all the enterprise domains with a single-valued database, pattern portfolio instances are populated for each of the domains: product, materials, process, equipment, etc. At a given time in the innovation cycle, these portfolios will explicitly reflect the degree of (often to be expected) inconsistency between the current status of the different portfolios, which may span time periods from late-stage current projects to longer-term master plans for future products, materials, and technologies. The benefit of this approach is that the information in the different portfolios has been structured by the S* Metamodel so as to make the comparability high.

S* Patterns for materials, material handling systems, manufacturing processes and equipment, packages and packaging systems, and products have been developed by enterprises across a diverse range of markets and technologies. The S* Metamodel has been tested and found to be stable across aerospace, consumer packaged goods, pharmaceuticals, medical devices, on and off road vehicles and equipment, and other segments.

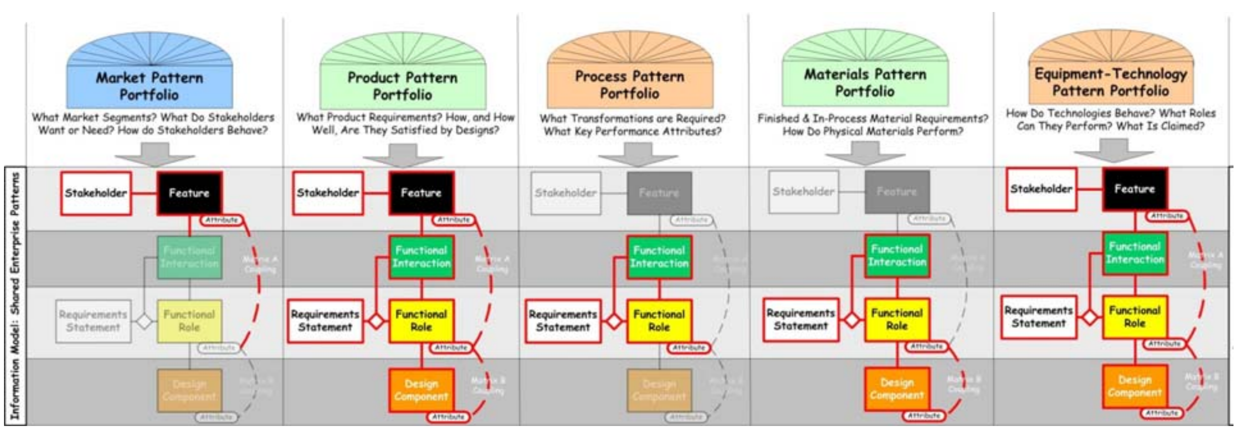


Figure 15. Pattern-Based Systems Engineering (PBSE)

5. CONCLUSIONS

Applying this PBSE approach to manufacturing systems has been found to help:

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”.

7. Improve the ability to perform long-range planning and portfolio management of manufacturing technologies, along with related product science and technologies.
8. Organize patterns of re-usable IP for processes, materials, technology, and design.

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