Building Models of Product Development Processes: An Integrative Approach to Managing Organizational Knowledge

Tyson R. Browning
Neeley School of Business
Texas Christian University
TCU Box 298530
Fort Worth, TX 76129 USA
t.browning@tcu.edu

This is a preprint of a paper forthcoming in 2018 in *Systems Engineering*

The concepts in this paper have developed over the past 20 years with the benefit of many interactions with colleagues in industry and academia. I am also grateful for research support from a Neeley School of Business Research Excellence Award. As this work relates to many of my prior publications, please forgive the unusually large number of self-citations.

Building Models of Product Development Processes: An Integrative Approach to Managing Organizational Knowledge

The process for designing and developing complex system products—all of the activities performed and the information and other work products produced—is essential to innovative and competitive enterprises. This process is dynamic, complex, and complicated, and the people who understand it best are in short supply and may not be around for the next project. For a variety of reasons, models of this process are important to systems engineers and managers. A 2006 paper in this journal discussed key concepts in modeling product development (PD) processes. This paper follows by presenting a general approach to building PD process models, *integrative process modeling* (IPM), that support a wide variety of purposes, such as providing evidence for external certifications, planning projects and programs, and more—but especially serving as a salient repository for crucial organizational information. Although a centralized team of modeling experts leads the overall IPM endeavor, distributed agents define various processes and activities, thereby capturing PD information across very large organizations. The paper discusses management of the model-building project and subsequent operations, as well as software tool support and model storage. A collection of helpful heuristics guides IPM to help organizations improve the long-term value provided by PD process modeling.

Keywords: *Process modeling*, *product development*, *knowledge management*, *system design*, *engineering management*, *project management*, *program management*

1. Introduction

According to management guru Peter Drucker, "Knowledge is the only meaningful resource today. The traditional 'factors of production' have not disappeared, but they have become secondary" [Drucker, 1993, p. 42]. However, "although an organization's knowledge base may be its single most important asset, its very intangibility makes it difficult to manage systematically" [Bohn, 1994, p. 61]. A crucial set of knowledge in enterprises is what work to do and how to do it in order to get desired results. Over the past several decades, engineers, managers, researchers, and others have sought to model how various business processes transpire [e.g., Recker and Mendling, 2016; Wynn and Clarkson, 2017]. The concerns motivating such efforts have varied. In the areas of engineering design, systems engineering (SE), and product development (PD), needs for external certifications, process improvement, project planning, or knowledge management have provided an impetus for practitioners to invest resources in process modeling [Browning and Ramasesh, 2007]. Many enterprises have described, prescribed, defined, mapped, or modeled processes to satisfy customers, assessors, auditors, and executives. Some enterprises have realized that, with so much expertise retiring or leaving, *it is imperative to capture information about how complex systems of PD work lead to desired outcomes*. Digitizing and "mapping the genome" of PD work holds great potential for improving our understanding and management of it, especially when the "DNA" of previous, effective projects and programs is highly instructive and in danger of being lost. Practitioner terminology such as "process assets" and "process capital" reveals the imputed value of organizational process information [e.g., Matthies, 2014]. However, many investments in such efforts fail to provide the desired returns: many process modeling and knowledge management efforts seem to fizzle out without much long-term benefit or impact. Perhaps we need better approaches, because processes continue play a key role in contemporary SE research and practice, and the right kind of organized, process information—that captures the interfaces or "white space" between better-known activities—provides huge leverage for improving project outcomes.

A previous article in this journal [Browning et al., 2006]—strongly recommended as background reading—illuminated several essential concepts and motivations for modeling processes in the realm of systems design and development, or, more generally, product (and service) development. It differentiated PD processes from other business processes while distinguishing (but not addressing) three further areas of importance: building, representing, and using PD process models. The present paper stands on that foundation to advance best and next practices for the first of these topics—*building* PD process models that more fully support the gamut of uses, purposes, and concerns. The proposed methodology synthesizes industrial practices—influenced especially by the aerospace, automotive, construction, and naval ship design industries—with systems-oriented approaches from the literature. Although building a useful PD process model remains partly an art, this paper contributes a structured, systematic methodology that overcomes many lurking pitfalls and problems. The approach, *integrative process modeling* (IPM), stands a much better chance of providing long-term value to organizations. The main point of the resulting models is not to satisfy customers or auditors (although they can certainly do so) but rather to capture, organize, adapt, and evolve valuable, hard-earned information about what work to do and how to do it when developing a complex system—vital knowledge that is otherwise spread thinly across many people in a large enterprise.

2. Background

A process is "an organized group of related activities that work together to create a result of value" [Hammer, 2001]. A model is an abstract representation of reality—built, verified, analyzed, and manipulated for a particular purpose [Steiger, 1998]. An enormous literature exists on process modeling. The majority of this literature addresses "business process modeling" within the larger literature on business process management (BPM) [e.g., Malone et al., 2003; Aguilar-Savén, 2004; Marjanovic and Freeze, 2012; Recker and Mendling, 2016; Klun and Trkman, 2017]. Although this literature is highly detailed and insightful, it largely ignores the distinct characteristics of PD processes that call for particular approaches to process modeling.

A second stream of literature has focused on engineering design and PD, where researchers have developed numerous models that treat the PD process as a network of activities (work packages, analyses, decisions, events, etc.) with input-output relationships (deliverables, work products, information, data, documents, estimates, prototypes, materials, etc.). Browning and Ramasesh [2007] reviewed PD process models in this area; Wynn and Clarkson [2017] provided another a recent review. These models account for key differences between PD and general business processes, such as: (1) the intent to do something new, once (e.g., design a product) rather than the same thing repeatedly (e.g., take an order, assemble a product, provide a service); (2) the primacy of information as the basis for activity dependencies; (3) the highly cross-functional and transdisciplinary nature of integrated PD; (4) the greater propensity for parallel, overlapping activities (concurrent engineering); (5) the conditions of higher uncertainty and ambiguity; and (6) the need for greater flexibility and agility in process planning and execution [Reinertsen, 1997; O'Donovan et al., 2005; Browning et al., 2006]. Although the PD process modeling literature still has much to learn from the general BPM literature (and vice versa), the distinct characteristics of PD processes argue for basing an approach to building PD process models mainly on this second stream.

Browning et al. [2006] addressed some foundational issues in PD process modeling, tackling questions such as the following. Why build PD process models? What is the basis of PD process modeling theory? Is it even reasonable to attempt to model a creative process like PD? Why treat processes as a kind of system? What are the main frameworks available for building PD process models? Why is it essential that a process model account for both activities and their relationships (i.e., information flow, deliverables, and work products)? What are the general requirements and objectives for any PD process model? What are the differences between: (1) descriptive and prescriptive models, (2) standard and deployed processes, (3) "as-is" and "to-be" process models, and (4) centralized and decentralized process modeling? How should we deal with multi-phase or multi-stage processes—e.g., conceptual design, preliminary design, and detailed design? How can we address unknown unknowns—i.e., tasks and relationships we cannot foresee? How should we handle cynicism and resistance to process modeling among some workers? What is the basis for a generalized framework for PD process models? Their answers to these questions set the stage for the model-building approach presented in this paper.

Informed by systems theory, design theory, and coordination theory, the generalized approach to process modeling is based on activities (actions) and their interfaces (interactions)—an instantiation of the general approach to modeling the structure of any system of elements and relationships [Malone et al., 1999; Pall, 1999; Park and Cutkosky, 1999; Browning, 2002; Browning et al., 2006; Panchal et al., 2009]. To represent these, the generalized framework uses two basic objects, *process elements* (PEs) and *deliverables*.[1] Figure 1 shows the types of relationships between these two objects, each of which can have many attributes or properties (e.g., columns three and four of Table 1). Modelers may add further objects, such as tools and organizational units, as well as further attributes for each object.[2] Rather than jumping directly to a particular modeling framework or representation format (e.g., those listed in the second column of Table 1), the generalized framework guides development of a rich model that sits in the background and from which can be drawn the data needed to populate any desired view—a *process architecture framework* (PAF) approach [Browning, 2009, 2010, 2013]. Crucially, the PAF approach overcomes the typical tradeoff between model simplicity and completeness by building and using a rich model through simpler views. The IPM approach presented in this paper builds a generalized model, symbiotic with the PAF and renderable in other frameworks, formats, languages, or views for users with various use cases, purposes, or concerns. IPM takes a system-of-systems view of the PD process and enables the process model to adapt and co-evolve with the actual process. IPM objects and attributes may be modeled with business process modeling notation (BPMN), unified modeling language (UML [e.g., Bock, 2006]), systems modeling language (SysML [e.g., Friedenthal et al., 2014]), object-process methodology (OPM [Dori, 2002]), or other object-oriented frameworks, although using one of these languages is not a requirement (and this paper deliberately avoids diving into the formalisms of notation, class diagrams, etc.). Grounded in a solid theoretical foundation, this paper emphasizes practical guidance for *building* rich, flexible, configurable, tailorable, adaptable, and extendable models. We could say much more about *representing* and *using* process models, once built, but these two important areas lie outside the scope of the present paper.

It is important to reiterate that a process model should be distinct from, and need not depend on, any particular view of it, such as a flowchart. While a modeler's preferred view provides a medium for model building, any view so employed cannot be allowed to constrain the model by inappropriately anchoring and constraining the modeler's perspective. Each view has limitations that threaten to do so. For example, flowcharting conventions underemphasize the arrows (deliverables) among the boxes (activities), failing to compel even naming them. The desire for neatness in flowcharts tends to curtail accounting for activities' copious inputs and outputs, guiding modelers to settle for a single input to and output from each box, whereas PD processes realistically entail a complex web of interactions [Browning, 2002]. Thus, developing a process model through a variety of lenses—transitioning among several views—provides

[1] The terms "process" and "activity" are essentially interchangeable from a system perspective: any activity is a process, and vice versa. This paper will use the terms either as synonyms or relatively to each other—e.g., a process decomposed into activities. As this approach sometimes causes confusion, the generic term PE [e.g., Curtis et al., 1992] is used for any process, activity, sub-process, work package, task, step, etc.

[2] The generalized process model captures tools and organizational units as they map to PE and deliverable objects. An extended, *project* or *capability model* uses separate objects (with attributes) for tools and organizational units and replaces their appearances in PE and deliverable attributes with links to these objects. Such a model may also add still other objects (each with attributes) such as events, users, issues, resources, and goals.

superior capabilities for model integration, verification, and validation, especially since various stakeholders will find particular views more intuitive and insightful. IPM seeks to avoid some of the pitfalls of other model-building methods by synthesizing the advantages of several approaches.

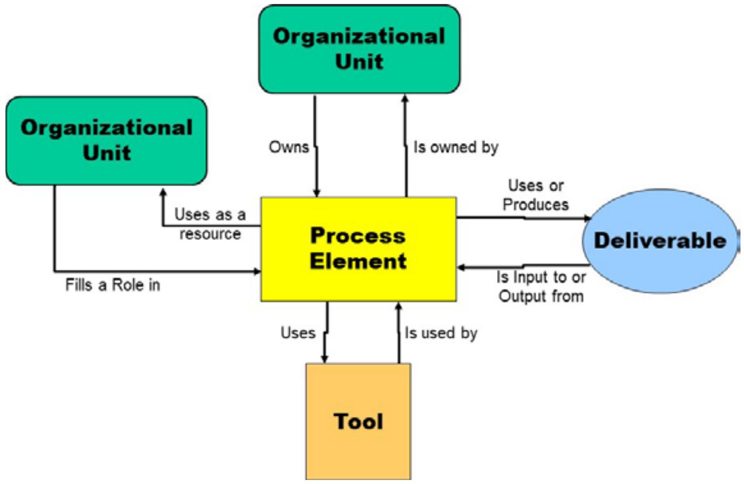


Figure 1: Types of relationships among some modeling objects

Table 1: Process model purposes, views, and information attributes (adapted from [Browning, 2009], which explains each item). (Bulleted items do not map across rows.)

Purposes (Use Cases, Concerns)	Views	Process Element (PE) Attributes	Deliverable Attributes
• Define standard and preferred activities • Define standard deliverables and quality standards • Define standard handoffs and structure standard work flows • Define standard tools and templates • Define standard staffing, roles, responsibilities, and skills • Visualize, understand, analyze, and improve processes • Identify "ripple effects" of process changes • Organize "knowledge" (information) about work • Tailor the standard process to suit project requirements • Filter activities and deliverables (by hardware vs. software, project size and phase, contract type, etc.) • Associate processes with elements of the project's work breakdown structure (WBS) • Identify appropriate activities and deliverables for the project • Import deployed process activities into a project scheduling tool • Define deployed deliverables and quality levels • Choose tools and templates • Set project schedule and secure formal commitments • Identify skill (or clearance) gaps in the workforce • Estimate project time, cost, quality, and risks • Allocate resources • Visualize planned work flows and integration points • Assign activity roles and responsibilities (staffing) • Monitor project status in terms of activities and deliverables • Renegotiate commitments where necessary • Access "knowledge" (information) about activities, tools, and deliverables • Deposit lessons learned • View practices relevant to a given standard • Confirm performance of requisite practices • Confirm production of appropriate deliverables	• Process flowchart –Network diagram –PERT chart –Activity-on-node diagram • Gantt chart • Design Structure Matrix (DSM) • Graphical Evaluation and Review Technique (GERT) • Textual Narrative • IDEF0 • IDEF3 • State diagram –Event graph –Markov chain –Data flow diagram –Directed graph • Create-Read-Update-Delete (CRUD) table • Value Stream Map (VSM) • Supplier-Input-Process-Output-Customer (SIPOC) chart –IPO diagram • Entry-Task-Validation-Exit (ETVX) diagram • Extended Event-driven Process Chain (eEPC) • Responsibility Assignment Matrix (RAM) –RACI chart • Work Product Standard (WPS) database record • Etc.	• Name • Parent • Constituents ("Children") • Mode • Shadowing • Deployment • Version Number • Brief Description • Inputs • Outputs • Entry Criteria • Exit Criteria • Verifications • Standard Process Metrics • Deployed Process Metrics • Tools • Standard Roles • Deployed Roles • Basis for Requirement • Rules • References • Standard Risks • Deployed Risks • Narrative Description • Tailoring Guidance • System Identification Number • WBS Element Association • Master Owner • Standard Owner • Deployed Owner • Change History • Change Notifications • Etc.	• Name • Parent • Constituents ("Children") • Mode • Shadowing • Deployment • Version Number • Brief Description • Suppliers • Customers • Key Criteria and Measures of Effectiveness • Requirements • Acceptance Criteria • Standard Process Metrics • Deployed Process Metrics • Format • Medium • Artifact • Rules • References • Narrative Description • Tailoring Guidance • System Identification Number • WBS Element Association • Change History • Change Notifications • Etc.

3. Building the Integrative Process Model

W. Edwards Deming famously stated, “If you can’t define what you do as a process, you don’t know what your job is.” Yet, no single individual could well describe all of the detailed tasks required to design and develop today’s complex systems. That is part of the challenge of modeling PD processes, but it is also one of the main reasons for doing so. Because no one person knows everything about all of the work (and even if they did, could not efficiently do or document all of it), it is important to capture and integrate the “system-level” knowledge[3] of many individuals into a single map of PE work. Hence, capturing, organizing, enriching, verifying, and validating process information form the essential backbone of the model-building process.

IPM describes an existing, “as-is” process. It does not (initially) prescribe a desired, “to-be” process. As Browning et al. [2006] explained, a descriptive process model, built inductively, captures information from tacit knowledge about how work actually occurs, whereas a prescriptive process model, built deductively, tells people what work to do. Prescriptive models become appropriate only once a process is well understood as a holistic system. After sufficient enrichment, integration, synchronization, verification, and validation, descriptive process models eventually become useful for generating (partial) prescriptions for future work. Ultimately, the model must be interactive and dynamic, and it must co-evolve with the organization and its projects.[4] While this paper provides the basis for approaching a high level of process *model* capability and maturity, its scope does not include important topics pertaining to the later *usage* of process models, once built.

In consultation with key stakeholders, a *core modeling team* (CMT) will direct the IPM process, although they should ultimately perform only a minority of the overall modeling work. Rather, they will distribute IPM work throughout the PD organization. Distributing IPM enables a much larger portion of the organization to achieve a shared interpretation of PD work and its description. It draws on the knowledge of the many rather than the few.

Figure 2 depicts the IPM process in a format aligned with the SE “V” model [Forsberg et al., 2005]. Generally, IPM begins with recursive structuring, description, and integration through greater levels of richness and detail. Although formal verification and validation occur towards the end, they ensue implicitly

---

[3] Information systems store information, not knowledge. Nevertheless, the term “knowledge management” is widely used to refer to methods and tools for storing and benefiting from information gathered from the knowledge of individuals. However, the capability of IPM to prompt reflection, critical evaluation, and comparison of perspectives provides a powerful mechanism for capturing richer process information from individuals’ knowledge.

[4] Many process models tend to deteriorate and depreciate over time, because they were produced and put to use (if at all) on the sidelines of “real work.” Rather, IPM intends to develop a model unobtrusively woven into the fabric of real work by providing value to (creating pull from) those doing PD work—e.g., as a manager plans or replans activity start and completion times, as team leads renegotiate deadlines within the context of a larger project, and as engineers look for relevant information to perform their tasks.

throughout. Moreover, although the diagram depicts a linear process, IPM, like PD, is actually highly recursive and iterative. The following subsections describe the steps along with helpful heuristics. Before beginning the IPM process, the CMT and an appropriate IPM information system (IPMIS) tool (see section 5) should be in place.

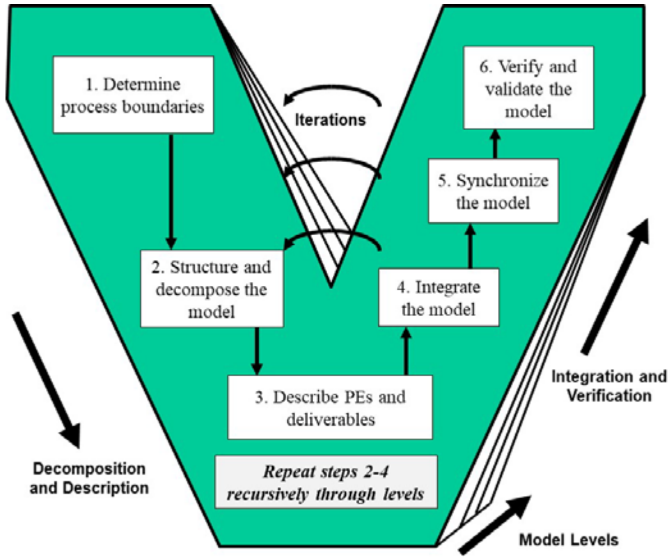


Figure 2: The IPM process depicted as a "V" model (adapted from [Forsberg et al., 2005])

3.1 IPM Step 1: Determine Process Boundaries

When modeling a process, it is essential to specify the limits of the work it describes. All systems (less than the universe) are part of a larger system (or systems). The same principle holds for processes (systems of work). The SE community has experienced numerous debates over the years about how to determine a system's boundary. As a kind of complex system, PD processes are not exempt from these challenges. Nevertheless, answers to the following questions can help solidify the PD process's *initial* scope and boundary: What is the desired result of the PD process? (Usually, it is a "recipe" for a product [Reinertsen, 1999].[5]) What are the last activities to occur before that result? What are the first activities in the PD process? What external inputs are necessary for those activities to begin? What related activities are *not* part of the PD process?

Maintain focus on the work required *for PD*. Starting with identified customer needs, PD activities gather, create, evaluate, and transform information and make decisions. A myriad of disciplines (e.g., marketing, engineering, manufacturing, procurement, finance, accounting, management) work together to

---

[5] A product "recipe" specifies the ingredients and instructions required to produce the product. It may take the form of "build-to packages" that specify the product's components and assemblies in terms of computer models, bill of materials, work instructions, machine tool instructions/programming, etc. It also includes design of the product's manufacturing, supply, distribution, and support systems.

deliver the recipe. However, the organizations and people involved in PD also do other work. These other activities should not be confused with PD work nor included in the PD process model. General infrastructure activities—such as those providing human resources, information technologies, capital equipment, and other enablers to all enterprise operations—are best left as external to PD, despite its reliance upon them.

Boundaries depend on many variables, so bounding remains somewhat of an art. Good heuristics can be helpful here, including those useful for bounding product systems [q.v., Rechtin, 1991]. Stakeholder agreement on a *tentative* boundary definition is desirable. An initial boundary must be set to get on with the modeling, but this boundary must remain malleable during IPM, which should repeatedly stress test the boundary definition. No model is perfect, so modelers and their sponsors must fight the temptation to over-analyze at this point. The output of this first IPM step is an initial definition of the root PE "Develop Product." Some of its attributes (see Table 2) may wait for later definition (as a roll-up of lower-level PEs), but for now it is essential to capture the PD process's scope and boundary (in the Brief Description attribute) as well as its external inputs and outputs.

3.2 IPM Step 2: Structure and Decompose (Architect) the Model

3.2.1 Decompose (Enrich) the Model

We now turn from the external boundaries of the PD process to its internal structure. To understand and model the PD work, we begin by decomposing the root PE into smaller PEs. A PE describes a piece of work done to produce a result. When describing a PE, it is critical to keep its desired result (why it exists) in mind. Figure 3 illustrates the concept of describing work at abstract and detailed levels in terms of PEs. At level *x*, the model describes a large scope of work holistically, in general terms, whereas level *x*+1 describes the same work in greater richness by parsing it into several pieces, each of narrower scope and greater specificity. The higher the level number, the greater the detail.[6] Crucially, *each (complete) level of decomposition should holistically describe the entire process*. The PEs at each level should collectively describe *all* of the work done to get the result. The (complete) levels differ in abstraction and richness of description, *not scope*. Despite the decreasing size of each box (PE) in Figure 3 with increasing level number, each PE should contain approximately the same amount of information. Thus, the total information content at each (complete) successive level will increase geometrically. Decomposition may continue through as many levels as needed; section 3.5 will discuss appropriate limits.[7] Some parts of the process may require deeper decomposition (richer definition) than others. In Figure 3, for example, PE 1.2 requires

[6] Confusingly, convention dictates that lower levels of decomposition have higher level numbers—notwithstanding that a "level 1" (root) process is often referred to as a "high level" process. Some have therefore suggested inverting the scheme by using "level *x*" for the most detailed processes and "level 10" [or whatever] for the highest, root node. The problem here is that the top level is fixed while the bottom level, as we will discuss later, may vary.
[7] For general guidance on decomposing complex systems, see [Courtois, 1985; Simon, 1996; Bahill et al., 2005].

further breakdown, whereas the other PEs at its level do not. (Hence, level *x*+2 is not complete.) However, selective decomposition decisions typically do not become an issue until several levels below the top (root) level.

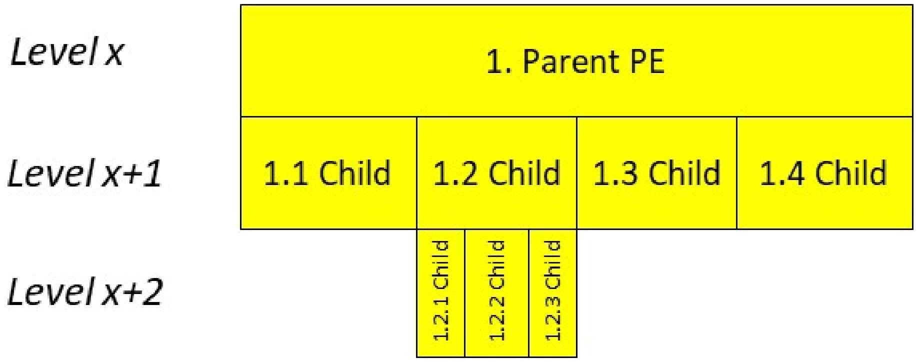


Figure 3: Describing work at abstract and detailed levels through decomposition into PEs

Modelers should consider alternative avenues for decomposition. Should the PD process be broken down temporally, into phases or stages? Alternatively, should it be parsed into parallel "swim lanes" or threads, each flowing from beginning to end? A hybrid approach works well: decompose first into temporal stages (such as conceptual design, preliminary design, and detailed design), then into parallel, discipline-oriented threads, and then again temporally. Because the model seeks to describe the "as-is" state, existing work breakdown structure (WBS) documentation could provide a useful input. Be sure to account for important decision gates and milestones.

The intent of process decomposition is not to promote reductionist thinking. IPM does not treat each PE in isolation; it emphasizes integration and verification, and the emergence and validation of holistic process behavior. Decomposition provides a "structural model" [Hubbard, 2009] of the *process architecture* [Browning and Eppinger, 2002], "the structure of a process—embodied in its activities and their interactions with each other and the process environment—and the principles guiding its design and evolution" [Eppinger and Browning, 2012]. As with setting process boundaries, effective process architecting and decomposition remain somewhat of an art. Decomposition choices reflect assumptions about the structure of the work at the next-lower level; subsequent integration will force reconsideration of such assumptions.

Heuristic 1: Each decomposed, "parent" PE should contain 2-20 "children," typically between 8-12. (The terms "parent" and "child" refer to relatively higher- and lower-level PEs in the decomposition, respectively.) Two is the minimum number of children for decomposition, whereas 20 is a rough upper bound on a manageable group of elements—e.g., the number of flowchart boxes fitting on a typical page or screen. If more than 20 children seem necessary, look for ways to consolidate into groups while anticipating further decomposition later (which would describe the 2-20 children as 4-400 "grandchildren").

We will consider further decomposition in section 3.5, but, in this initial decomposition, we seek to define just the immediate next level, usually about 8-12 PEs constituting the overall process.

Heuristic 2: At each level of decomposition, define PEs of similar size (at least within an order of magnitude) in terms of required work. For example, avoid decomposing into ten children if five require 1,000 labor hours each and five require 100,000 labor hours each. At high levels of the model, many PEs may culminate in milestone events, which may not require much direct work in themselves; hence, they might not be listed as distinct PEs until lower levels of the model. For example, a high-level PE called "Create Preliminary Design" could reasonably include a preliminary design review event.

Heuristic 3: PD consists of definable actions, decisions, and interactions. Wherever possible, decompose PEs into discrete activities with clear results. Avoid defining ongoing, "level of effort" PEs that span the PD project. Seek to punctuate ongoing work such as stakeholder engagement, SE, and project management into discrete PEs that produce specific results at various points in the PD process. This guidance becomes more essential at deeper levels of decomposition.

Heuristic 4: Many SE and project management activities occur throughout the PD process, so they should not be withdrawn into a separate SE PE. For example, if activities such as defining requirements, planning and managing technical effort and performance, trade studies, and verification, validation, and testing (VVT) occur as part of every subsystem and component design process, then that is where they should reside. Rather than exist as a stand-alone, parallel PE, infuse SE activities into all appropriate PEs.

3.2.2 Assign PE Owners

After decomposing the overall process into 2-20 children, the CMT must designate the owner of each. This owner should be the executive or high-level manager responsible for the work performed within the PE. Formal, preassigned organizational responsibility for the work will usually facilitate this determination. If the process decomposition does not align with the organization's existing structure, however, the CMT may have to arrange new ownership. For now, it is important to establish a point of contact for the delegation of further process definition. Ideally, a functional/core representative responsible for the "standard" work should own a PE. While leading the modeling work for their PE, functional owners should consult with those actually doing the work on any ongoing projects.

Heuristic 5: As much as possible, (1) assign each PE at a given model level to a different owner, and (2) assign ownership at the lowest possible organizational level with purview over the work. For example, if a single director oversees several same-level PEs, assign each of them to a different senior manager (reporting to the director) rather than just assigning all of them to the director.

The reason for assigning PE owners during this early step is to facilitate decentralized, distributed process modeling [Browning et al., 2006]. PD process models quickly become complex and complicated [Ramasesh and Browning, 2014]. The amount of information to gather and manage will simply overwhelm the CMT (and the overall organization may not "buy in" to its result). It is therefore better to have many people (those closest to the actual work) each contributing a little to the model, with the CMT providing a leadership and integration role. Expecting the CMT alone to model the entire PD process of a large, complex organization creates an enormous bottleneck of effort and expertise, resulting in shallow models. In addition, cascading responsibility for PEs throughout the organization enables faster updating and maintenance—the further capture of new information as it becomes available. Distributing the IPM work throughout the organization helps overcome some of the main reasons why many PD process modeling initiatives have provided very limited long-term value.

3.2.3 Summary of Step 2

For the initial completion of IPM step 2, the CMT should have as its output a set of 2-20 (probably 8-12) Level 2 PEs that represent the entire PD process. Each PE should have an assigned owner who will further define it in step 3. (Section 3.5 will discuss further decomposition into lower levels.)

3.3 IPM Step 3: Describe the PEs and Deliverables

3.3.1 Step 3.1: Describe PEs' Basic Attributes

In this IPM step, each PE owner begins to capture and describe attributes of the work. In most cases, especially for high-level PEs (level numbers less than five), this owner will act more as a leader who assembles his or her own small team of modelers, which will need some of the process modeling skills epitomized in the CMT. For this reason, the CMT should have qualified PD process modeling consultants available to assist each PE owner and serve as a facilitator for his or her modeling team.

The third column of Table 1 lists many PE attributes, but not all of these require initial capture. Table 2 provides guidance for capturing the foundational ones. To decompose a PE (break down its work) and gather the relevant information, the PE owner's modeling team may need to call upon additional subject matter experts (SMEs). As this work proceeds, the CMT must guide PE owners to ensure consistency within their PE attributes—e.g., between typical role and resource amounts and Duration measures.

Experienced modelers of processes will recognize that this sub-step involves creating a supplier-input-process-output-customer (SIPOC) chart for each level 2 PE. PE owners may indeed use such a format if they desire. However, it is imperative that they not allow the information to reside only on electronic paper, slides, or spreadsheets: it must go into the IPMIS.

3.3.2 Step 3.2: Describe Deliverables' Basic Attributes

Next, the PE owner's team begins to capture and describe the attributes of the work products, the deliverables flowing to and from the PEs (the "arrows" among the "boxes"). Unfortunately, deliverables are underrepresented in most process models, especially those based on flowcharts [Browning, 2002]. As an essential part of any systems-oriented process model [Parris, 1996; Howard, 1998; Lykins et al., 1998; Halpern, 1999], however, the deliverables (the process system's "interfaces") provide the basis for the architectural patterns of workflow and overall process behaviors. For each of the PE's inputs and outputs identified in Step 3.1, collect the basic attributes in Table 3. Each deliverable has one or more key criteria

Table 2: Guidance for capturing basic attributes of PEs (most described in [Browning, 2009])

WBS	Work breakdown structure (WBS) number, such as "1.3," for use as a shorthand reference
Name	Although each PE should already have a name assigned in Step 2, the PE owner may want to improve it. PEs imply action, so name each with a verb phrase [Mendling et al., 2010], such as "Develop requirements" or "Analyze weights."
Standard Owner	Name of the PE's owner, as assigned in Step 2
Parent[a]	Name of the parent PE (level x-1)
Children[a] **(and Owners)**	Follow the guidance in section 3.2 to decompose the PE to level x+1, identifying 2-20 constituent PEs that collectively perform all of the work of this PE. Name each with a verb phrase. Assign each an owner. For now, simply record this information as a bulleted list. (When choosing against further decomposition, modelers may list further details of work steps in the PE's Brief Description attribute.)
Brief Description	Write a paragraph describing the purpose of the PE and any of its key features. Low-level PEs without children may here list steps or link to procedures or manuals where applicable.
Inputs[b] **(and Supplier**[a]**)**	Make a bulleted list of the deliverables used by the PE. Do not include resources (personnel, facilities, tools, etc.), which will be captured separately. By each input, identify its source/supplier as the name of another PE within the PD process, or else as "External." Do *not* include deliverables created and consumed only and entirely *within* this PE (i.e., among its children). **Heuristic 6:** Wherever possible, try to have only one supplier for each input. Where this is difficult, try making the name of the input more specific. For example, if the input "Requirements" comes from three different sources, try listing a separate input for each: "Weight requirements," "Size requirements," and "Material requirements." However, it will be necessary to list multiple suppliers in cases where a choice of suppliers exists. **Heuristic 7:** Select the supplier PE at the lowest possible level. Initially, that will be Level 2, but as deeper levels of decomposition develop, reroute an input from a supplier's child, once defined.
Outputs[b] **(and Consumers**[a]**)**	Make a bulleted list of the deliverables produced by the PE. For each, identify its destination/receiver as the name of another PE within the PD process, or else as "External." Do *not* include deliverables created and consumed only and entirely *within* this PE. A single output may go to more than one customer. As with suppliers of inputs, select the consumer of an output at the lowest possible level, and later reroute an output to a consumer's child, where available and appropriate.
Entry Criteria	Make a bulleted list of the events *and* conditions that should exist and the required maturity levels of the inputs for the PE to begin execution. Starting the PE without meeting these criteria incurs additional risks (which modelers may also list). Include events that signal the beginning of the execution of the PE, such as authorizations and directions. It may help to parse this attribute into (A) triggering events and (B) requisite conditions for PE to begin.
Standard Roles	Make a bulleted list of the personnel roles required to execute this PE [Murdoch et al., 2001]. For each role, note the number of individuals typically required and its functional/discipline home organization (if relevant). Delineate roles such as, e.g., "Team Lead" (from the Project Management function) or "Structural Analyst" (from the Engineering function). It is often helpful to distinguish varied skill levels as different roles, such as "Structural Analyst (junior)" and "Structural Analyst (senior)." Modelers may keep this attribute quite general for high-level PEs, but they must detail it carefully for the lowest-level PEs. Check for consistency between each parent PE and its children in terms of aggregate roles and numbers. (A good software tool for IPM would do this automatically.) The CMT should develop a master list of roles from which PE owners may select (or propose additions).
Tools	Make a bulleted list of the tools used during the execution of this PE. Include any forms, templates, hardware, software, information systems, etc. that help in gathering, processing, or formatting information, inputs, or outputs. List things that someone doing the work would use, rely on, or find helpful in achieving the desired result. Avoid over-specificity, such as naming particular software tool brands, focusing instead on the tool's function. Modelers may keep this attribute quite general for high-level PEs, but they must detail it carefully for the lowest-level PEs. Check for consistency between each parent PE and its children in terms of aggregate resources. (A good IPMIS would do this automatically.) The CMT should develop a master list of tools from which PE owners may select (or propose additions).
Other Resources	Make a bulleted list of any other (non-human and non-tool) resources used by the PE.
Measures	• *Duration*: Estimate the typical duration of the PE on a typical project, assuming typical resources. Use consistent time units, such as days, across all PEs. This number may be adjusted later, but it is gathered at this point to facilitate sizing and comparing PEs. • Other measures may be added later. For example, *Cost* may be added here as an explicit measure, determined from the labor hours required to fulfill the standard roles and any other required resources and tools (but it is best *not* to include measures unless they will update automatically upon changes in their determining factors).

[a]PE names to be replaced with System Identification Numbers (SIDs) in the IPMIS [b]Deliverable names to be replaced with SIDs in the IPMIS

(KCs) that characterize its value to recipient(s)—i.e., customer value [Browning, 2003]. If needed for the purpose at hand, modelers may also capture any of the other attributes in the last column of Table 1.

Table 3: Guidance for capturing basic attributes of deliverables (most described in [Browning, 2009])

Name	Check the name given to each deliverable in Step 3.1 to ensure it is a noun phrase, such as "Size requirements" or "Weight estimates." It may be helpful to preface the name with a hierarchical identification number, such as "D2," for use as a shorthand reference. In some situations, it may be necessary to capture more than one name for a deliverable ("also known as"), although it is best to agree and standardize on one name.
Supplier[a]	Name of the deliverable's producer/source/supplier (already available from Step 3.1); use the name of another PE in the PD process, or else write "External—xxx," where "xxx" names a source outside the PD process, such as the final customer, a corporate office, an advanced research group, marketing, etc.
Consumers[a]	Name(s) of the deliverable's destination/receiver (already available from Step 3.1) ; use the name of another PE in the PD process, or else write "External—xxx," where "xxx" names a consumer outside the PD process, such as the final customer, a corporate office, the production process, etc.
Key Criteria (KCs) and Measures of Effectiveness (MoEs)	Make a bulleted list of the criteria by which the customers judge the effectiveness, quality, and usability of the deliverable—e.g., "Size," "Weight," etc. Always include "Availability," the time in the PD project when the deliverable becomes available, as a KC. KCs are similar to, and sometimes known as, critical-to-quality (CTQ) characteristics or key performance indicators (KPIs). One to five KCs typically suffice. For each KC, make a bulleted list of one or more ways to measure its performance—e.g., days for Availability, centimeters for Size, kilograms for Weight, etc. Each KC may also have associated estimates of its "Accuracy," "Precision," "Maturity," "Completeness," "Confidence" [e.g., Shapiro et al., 2016], etc.

[a]PE names to be replaced with System Identification Numbers (SIDs) in the IPMIS

This IPM step decomposes the overall PD process to Level 3, describing it in terms of 4-400 PEs. The owner of each of the 2-20 PEs at Level 2 will now have defined their PE in terms of the attributes in Table 2 and their PE's input and output deliverables in terms of the attributes in Table 3.

3.4 IPM Step 4: Integrate the Model

IPM step 2 distinguished the "puzzle pieces" that depict the PD process at Level 2, and step 3 then defined the content and shape of each piece. Now it is time to put the Level 2 puzzle together, making sure the pieces fit. However, many potential disconnects among the PEs make process integration non-trivial. Figure 4 gives an example of two PEs, each with defined input and output deliverables. At the integration step, the two PE owners realize (perhaps via prompting from the IPM software tool or the CMT) that the output "Preliminary Concept" is really the same thing as the input called "Initial Concept." This conclusion causes the two deliverables to become one, whose owners must negotiate its name and attributes (Table 3) [Scherr, 1993]. Different names for deliverables are only one of many potential problems encountered at this step. Orphan deliverables (no agreed supplier or customer) are also common. See [Browning, 2002, 2014] for an extensive list of integration challenges and further examples. Ideally, the IPMIS will have basic AI to flag obvious integration issues (such as where input-output lists among suppliers and customers do not match).

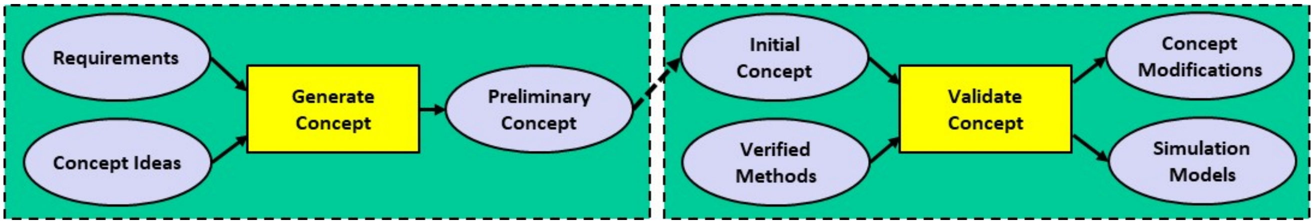


Figure 4: Example of process integration between two PEs [Adapted from Negele et al., 1999]

Many process modeling efforts tend to bog down at this step, because making time for discussions and negotiations among the PE owners is cumbersome. This is time well spent, however, and it is where IPM starts to pay dividends in the organization [Pall, 1999]. IPM serves as an integrative mechanism for streamlining coordination in future projects and helps instill a customer-value perspective throughout the PD process. It also unearths latent information in the organization about the process as a system—how PEs (which may be well described in themselves) work together to produce overall results—the "white space" interfaces ignored by many other modeling approaches. Nevertheless, managers can reduce the required efforts: they can approach integration discussions in various ways, some less effort-intensive than others.

Heuristic 8: Begin with minimal-effort, asynchronous tools such as e-mail prompts and web portals, which alert PE owners to integration issues and allow them to make obvious corrections and enhancements. Save effort-intensive, synchronous tools such as face-to-face meetings only for difficult issues, and ensure that such meetings proceed efficiently.

The process architecture emerges as the co-product of the decomposition in IPM step 2 and the integration in step 4. It now becomes possible to identify architectural patterns such as those formed by dependent, independent, and interdependent PEs. (We will discuss interdependent PEs further in IPM step 5.) Visualizing such patterns becomes easier with representations such as a design structure matrix (DSM) [Eppinger and Browning, 2012]. The DSM also provides an advantageous format for highlighting integration status (e.g., red or green shadings in the off-diagonal cells). PE and deliverable attributes may also spawn conditional or contingent relationships, such as when an input may come from one supplier or another, or when an output may go to one receiver or another. The Inputs, Outputs, and Entry Criteria attributes of PEs should note these situations.

Typically, process integration will reveal problems with previous definitions of PEs and deliverables. Where needed, adjust both accordingly, and/or add new ones. Clearly, changes to the process model will occur and eventually require formal control. An appropriate IPMIS is essential for automating simple updates, catching disconnects caused by changes, and alerting affected PE owners.

Upon completion of IPM step 4, each deliverable among the Level 2 PEs should be confirmed by its suppliers and consumers. Both should agree on its name and other attributes (Table 3).

3.5 Decompose Recursively

The initial pass through IPM steps 2-4 results in an integrated process model at level 2, with proposed decompositions for each of its 2-20 PEs at level 3. However, such a model will still be quite abstract, lacking the richness to describe the work of most people executing the process. It is therefore necessary to continue the process of decomposition, definition, and integration through successive levels, which entails revisiting steps 2-4 for level 3 and beyond.

3.5.1 Depth of Decomposition

How far should we decompose? How much detail is enough? This is a judgment call, but the following heuristics provide helpful guidance.

Heuristic 9: Decompose the work into sufficient detail so that it may be planned, executed, and monitored with confidence. In most cases, this requires that work eventually be broken down into PEs with durations of about 1-10 days. Depending on the size of the PD project, this may require 5-10 levels of PEs.

Heuristic 10: If including the important details of a PE requires more than a paragraph or so of descriptive text, then decompose it and capture the details in the descriptions of 2-20 children.

Heuristic 11: At any level of the model, a high ratio of deliverables to PEs may indicate the need for further decomposition, especially if any of the deliverables cause PE interdependencies (i.e., coupled blocks, discussed in section 3.6.1). Further decomposition may unravel apparent couplings at higher levels [Browning, 2002].

Heuristic 12: Most modelers (and managers) will readily decompose well-understood tasks while leaving ambiguous ones as "long bars on the Gantt chart"—i.e., long-duration, "level of effort," "figure it out as we go" tasks from which some kind of miraculous result will hopefully emerge. It is important to fight both of these urges, especially the second one. Straightforward, well-understood PEs may not require much further enrichment, whereas difficult, ambiguous, uncertain PEs merit the investment of effort to clarify what actually happens. The act of model building serves this purpose well. Decomposition and enrichment add the most value where they are most difficult.

Heuristic 13: Do not let the decomposition become overly prescriptive of dynamic work. Whereas higher-level PEs remain highly consistent across projects, lower-level PEs (with higher level numbers) tend to be more dynamic. Technologies, tools, methods, and possibilities for doing smaller pieces of work are more likely to change from one project to the next. In some such cases, it may not be helpful to define dynamic PEs at a highly detailed level. Each PE describes *what* to do to get its results; its children essentially describe *how* to do it. Thus, decomposition may essentially force answering the "how" question, although some may not think it appropriate to prescribe how.[8] IPM seeks to capture information from knowledge

[8] People may have different perceptions about whether a PE is stable or dynamic [e.g., Danner-Schröder and Geiger, 2016].

about PD work, but some of its smaller details may be worth it. As this heuristic may conflict with the previous one, however, modelers should not invoke it lightly, merely for the sake of avoiding work. Usually it is still important to know how work currently occurs, even in the face of impending changes.

Heuristic 14: When it seems like time to stop decomposing, go one level deeper to prove it. Most process models end decomposition prematurely. Having even an unofficial description of the next-lower level of work helps to understand the higher level better.

Heuristic 15: Any portion of work specified by a formal standard, regulation, directive, or policy usually merits distinction from other work.

As the modeling reaches deeper levels, process modelers will rely less on general knowledge and existing process documentation and more on interviews, real-time observations, recorded event logs [e.g., van der Aalst, 2010], and parameterized product models [e.g., Black et al., 1990]. Go to where people are actually doing the work. Hess et al. [2012] discussed some techniques for helping "end users" articulate their activities. Ask them "what," "how," and "why" questions. Look at the interfaces among the designed product components and their implications for design decisions and problem solving. Identify activities for defining, analyzing, evaluating, selecting, assessing, and reporting designs. Remind everyone to focus on describing the "as-is" process (while noting their great ideas for improving the process as a separate PE attribute—see section 4.5). Descriptive process modeling is discovery-driven. At this stage in the modeling, it is fine to use innovative ways to discover information about how work is done, but not to jump to trying to innovate better ways of doing it.

Heuristic 16: Seek to distinguish "subroutine" PEs—i.e., sub-processes or activities which occur in more than one time or place in the PD process. For example, several parts of the PD process may have their own requirements gathering, design review, configuration management, or risk management activities. Keep these instances separate in the model while noting their potential commonality, because defining each such PE distinctly within its area facilitates later opportunities for consolidation. Subroutine PEs do not tend to become prevalent until lower levels of decomposition, however.

Each complete level in the PE holarchy[9] is actually a full system model, describing the entire PD process in a particular amount of detail. Therefore, while a WBS or PE directory tree may depict the mere hierarchical decomposition, observers should not get the wrong impression from such a partial view. As noted with respect to Figure 3, not all PEs require equal amounts of enrichment; deeper levels of the PD process decomposition may be incomplete. For example, level 5 might be complete, with only selected PEs

---

[9] The PEs described in the generalized modeling framework share many properties of holons. "A holon is a system that is an evolving self-organizing dissipative structure, composed of other holons, whose structures exist at a balance point between chaos and order." A holarchy is "a hierarchy of self-regulating holons that function first as autonomous wholes in supra-ordination to their parts, secondly as dependent parts in sub-ordination to controls on higher levels, and thirdly in coordination with their local environment." (Wikipedia)

further defined at levels 6, 7, or below. It is also possible to work with a hierarchy of deliverables, as large deliverables break into sections, such as in the requirements example mentioned in Heuristic 5 (Table 2).

3.5.2 Deliverable "Pull Down"

As modelers define lower-level PEs, they must reassign the previously identified deliverables flowing among parent PEs. Because each level of the process model describes the entire PD process, modelers must capture the deliverable flow at the lowest possible level (from which higher-level deliverable flows can then be inferred). For example, Figure 5 shows two PEs, A1 and B1, each later decomposed. Reconsidering the previously identified deliverable flowing from A1 to B1, modelers determine that it more specifically flows from A1.3 to B1.1. Thus, they change the supplier and consumer of the deliverable accordingly. Of course, any view of the process model at the level of A1 and B1 must be able to scan any lower levels of the network to recognize and display any such implicit connections. Yet again, the right software tool is essential here. Such a tool would walk modelers through the rerouting of all deliverables at each level of decomposition. In some cases, modelers might need to replace a higher-level deliverable with two or more separate deliverables at a lower level.

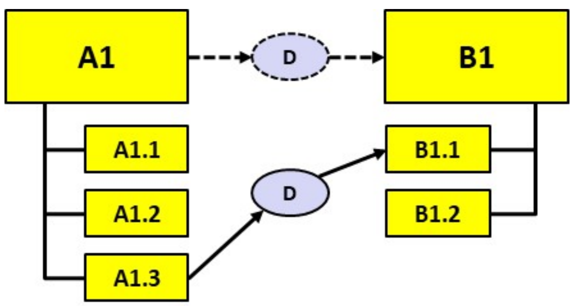


Figure 5: Example of rerouting a deliverable after PE decomposition

3.5.3 Summary

When the CMT and all PE owners agree on sufficient decomposition, description, and integration, the PD process model will consist of many linked PE and deliverable objects—in a large PD organization, probably thousands. A great many people throughout the organization should have roles as PE owners, allowing the model to capture information from the breadth and depth of the organization's PD process knowledge. The IPM effort itself will have generated much useful dialogue and coordination among these area experts, helping them to agree on ontologies and relationships. Nevertheless, everyone should view the working process model as a *theory* of the work required (and the interim and final deliverables produced) to design and develop a product. The model must remain open to change and improvement, especially over the next steps of the IPM process.

3.6 IPM Step 5: Synchronize the Model

Model integration ensures connectivity among the PEs in terms of agreed-to deliverables. The next

IPM step, process model synchronization, sorts out groups of interdependent PEs and works out temporal disconnects among the PEs, both horizontally (within levels) and vertically (across levels) in the process architecture. It requires gathering temporal attributes of each PE and deliverable, and analyzing and adjusting them as needed. It moves the PD process model another step closer to reality, making it useful for helping plan and manage future PD projects. It also helps verify and validate the model—causes further advanced in later IPM steps.

3.6.1 Dealing with Iterations and Rework

PD processes contain both planned and unplanned iterations of PEs. Eckert [2006] distinguished (1) repeating a PE to accomplish a different purpose from (2) repeating it to refine a design and from (3) reworking it to fix a problem. Planned iterations include design cycles or spiral development, where successive passes through similar activities enhance and refine the product design. However, all such work actually occurs in linear time, so modelers frequently ask if and how they should "unroll" planned iterations. This becomes especially challenging when the number of iterations is not predetermined. There are arguments for and against unrolling the iterations—i.e., attempting to distinguish each iteration temporally, as separate PEs (each of which may consist of several PE children). Unrolling becomes more helpful when the iterations are more substantially different from each other, and when the number of iterations is easier to predict. Unrolling is recommended at higher levels of the model—e.g., major design phases or sub-phases—to facilitate joint reviews and design integration activities. Leaving iterations as coupled groups of interdependent PEs [Eppinger and Browning, 2012] becomes more necessary, however, when iterations are poorly understood and breaking them down would require further, specific investments in process understanding and improvement. Estimating the duration of a group of coupled PEs becomes much more difficult, however.

Unplanned iterations and rework occur due to several reasons, such as: poor PE sequencing (creating deliverables later than other PEs need them); not supplying all of the needed deliverables; not transmitting a deliverable clearly, promptly, or appropriately; later changes to PE inputs; and, of course, mistakes (inadvertently creating defective deliverables) [Lévárdy and Browning, 2009]. Many characteristics of PD processes make iteration and rework inevitable. The IPM model makes it possible to account for feedback relationships (cycles or loops in the network structure), desirable or not, although these complicate the determination of temporal attributes. Although some modelers resist including rework for fear of somehow legitimizing it, the point of a descriptive model is to capture such situations as they currently exist and set the stage for later improvements. (Making such improvements, one of the many uses of a process model, is a topic for elsewhere.)

Heuristic 17: Inasmuch as possible, do not allow planned iterations to show in the top levels of the model. That is, do not cross major PD phases or stages with feedback loops. Modelers may need to revisit the choice of decomposition in step 2 to address some instances.

3.6.2 Applying the Critical Path Method (CPM)

IPM step 3.1 collected PE duration as a "Measures" attribute (Table 2). Now we add five more Measures to each PE: Earliest Start Time (EST), Earliest Finish Time (EFT), Latest Start Time (LST), Latest Finish Time (LFT), and Slack Time. We also use a KC, Availability, for each deliverable. We express all of these in "PD project time" with identical units (e.g., days). The project begins at time zero, with various PEs starting and ending and various (internal) deliverables becoming available thereafter. Starting with *only the lowest complete level* of the process model,[10] apply the CPM (preferably automated by the IPM software):

1. Estimate the Availability of all "External" input deliverables to the PD process in terms of time after process start. External inputs required to start the PD process have Availability = 0.
2. For each PE with Availability defined for all input deliverables, set EST equal to the maximum Availability among its inputs. At least one PE should have EST = 0.
3. For each PE with EST defined, set EFT = EST + Duration, and set the Availability of each of its output deliverables to its EFT. (Ideally, a software tool would automatically update the Availability of any deliverable output to equal the EFT of its supplying PE, although modelers could override this.)
4. Repeat steps 2-3 until all PEs have EST and EFT defined, and all deliverables have Availability defined.

The maximum EFT among all PEs sets the overall PD project duration. Store this as the Duration Measure of the root (highest level) PE. Then, to determine LST, LFT, and Slack Time for each PE in the lowest complete level of the process model, do a backwards pass through the network:

1. For each PE with only "External" consumers of its outputs, set LFT = overall PD project duration.
2. For each PE with LFT defined, set LST = LFT – Duration, and set Slack = LFT – EFT.
3. For each PE with LST defined for all of its successor PEs, set LFT equal to the minimum of the LSTs of its successors, set LST = LFT – Duration, and set Slack = LFT – EFT.
4. Repeat step 3 until all PEs have EST, LST, and Slack defined.

All PEs with Slack = 0 are defined as critical activities in the network. At least one thread of critical activities, called the critical path, will run through the network from beginning to end.

3.6.3 Ensuring Vertical and Horizontal Consistency

We now have six temporal measures defined as attributes of each PE at the lowest *complete* level of

[10] To apply the CPM properly at the lowest *complete* level of the process model, one must account for any implicit deliverables rerouted to lower levels of decomposition. For example, in Figure 4, to implement the CPM at the level of the two parent PEs, one must account for the implicit deliverable between them (explicit among their children) for purposes of calculating availabilities. Note also that the CPM cannot handle feedback loops in the network, so we ignore these temporarily.

the process model. At any lower levels, modelers may carefully apply a slightly modified version of the CPM to subsets of the overall process, bounded by the temporal attributes of the adjacent PEs. At the level immediately *above* the lowest complete level, confirm that the Duration of each parent PE equals the difference between the maximum EFT and minimum EST of its children.[11] Update and adjust as needed for consistency. A useful IPM software tool would automate such consistency checks and flag discrepancies.

PE owners will likely disagree about many deliverable Availabilities. The CMT must direct negotiations and adjustments. Drawing upon the example in Figure 4, suppose the owner of the Validate Concept PE needs the Initial Concept deliverable by day 100, but its Availability = 150 days. These two PE owners (and probably other affected owners as well) must negotiate the timing. Many possibiliites exist for working this out, including PE overlapping and crashing (see section 4). These negotiations will naturally include discussions about roles and resources, which may greatly affect PE durations. However, at this point, the PEs' temporal attributes remain somewhat conceptual: actual beginning and end times for each PE will be set later, when a deployed instance of the process becomes prescriptive. For now, process synchnonization serves as a reality and feasibility check for the model. Ultimately, actual situations and historical data provide the best basis for the attributes of the "as-is" PEs and deliverables.

3.6.4 Summary of Step 5

At the end of this IPM step, each PE and deliverable in the PD process model should have realistic temporal attributes with consistency across the PE holarchy.

3.7 IPM Step 6: Verify and Validate the Model

Throughout the process of building a hierarchical and networked model, many checks for accuracy, consistency, and correctness must occur. The IPM process prompts such confirmations at many points along the way. Thus, verification is largely an ongoing activity, constantly running in parallel with the previous steps. Significant validation also occurs as the many PE owners enrich the model with negotiated inputs and crosscheck the model against their own perceptions (mental models). As workers become accustomed to the model, their mental models begin to align with it over time. While they may not clearly articulate information about PE and deliverable attributes when the model is first built, they will be able to contribute improved information over time, making the model increasingly accurate. Again, the point for now is to ensure that the model sufficiently matches the reality of the "as-is" situation, while capturing opportunities for improvement as a separate PE attribute. Further validation will occur later, as the model is used.

Therefore, this step formally involves only asking each PE owner to confirm their PE's attributes and

[11] The CPM ignores feedback loops, so its duration calculations do not account for iterations and rework, which require more advanced estimating methods (see, e.g., [Browning and Eppinger, 2002]). At this point in the IPM process, modelers must make their best estimates of higher-level PE durations, using actual and historical data as well as CPM analyses of lower-level PE networks.

confirming that the IPM software tool does not flag any problematic situations (inconsistencies or disconnects) in the architecture. At the conclusion of this IPM step, the initial PD process model, and the PD process modeling *project*, are finished. Process modeling now ceases to be a finite project and gets added or absorbed into the ongoing operations of the firm. The process model will continue to evolve and improve, supported by full-time modeling experts who may act as change advisors and approvers, especially as the model is actively used. Many possibilities exist for using this process model, but these lie outside the scope of this paper.

4. Advanced Topics

The previous section sought to present the IPM steps concisely. However, most complex PD processes require additional modeling capabilities to capture and represent important characteristics. The IPM approach accommodates such needs. This section addresses how to deal with several advanced topics.

4.1 Multiple Versions of the Same Basic Activity—PE Modes

For several reasons, modelers may need to define alternative ways of accomplishing particular activities, such as a quick, low-fidelity version and a longer, high-fidelity version, or versions employing different tools, versions with different resources or roles, versions for different types of customers or contracts, versions with different inputs or outputs, etc. *PE modes* provide this capability. Each mode of a PE has a similar purpose, in general, but different attributes. For example, each of several ways to conduct a product test—evaluating a simulation model, testing a quickly fabricated prototype, or testing an actual piece of hardware—may have different inputs, entry criteria, roles, cost, duration, outputs, etc. Hence, a PE's mode of execution influences all of its other attributes. A PE may also have one or more specific iteration or rework modes, which may vary depending on what triggered the rework (i.e., different inputs). PE modes also provide a way to capture distinct scenarios for "crashing" (faster execution at varied expense), the use of alternative technologies and tools, and PE versions contingent on varied inputs. For an example application of PE modes, see [Lévárdy and Browning, 2009].

The Mode attribute distinguishes each version of a PE by providing a distinctive suffix to its name. Any PE with more than one mode must designate one of them (in this attribute) as the "chief" mode. By default, all other modes inherit the attributes of the chief mode (and any later changes thereto) except where overridden. Once a mode's attribute diverges from its chief, all future changes to that attribute must be considered across all modes (i.e., they cannot update automatically). To facilitate mode consistency, all of a PE's modes should have the same owner. Sometimes it is difficult to decide whether to add a mode to a PE or rather to define a separate PE, especially in situations of iteration (section 3.6.1). As with many modeling decisions, modelers may have to revise them later as part of model improvement.

4.2 Conditional or Contingent PEs

Modes provide a way to handle many situations with conditional or contingent relationships among

PEs, such as when the output of one PE goes to either of two others depending on specified criteria (sometimes categorized as “or” or “exclusive or” relationships). However, whether employing modes or not, such situations usually require the use of another PE attribute, “Exit Criteria” (Table 4), to specify the conditions. Conditional relationships among PEs also characterize many process variants. Methods exist [e.g., La Rosa et al., 2011] for consolidating as much of the common portion as possible.

4.3 Process Failure Modes and Effects Analysis (FMEA)

Process FMEA entails systematically querying each PE—especially PEs providing evaluations, tests, or reviews—about the consequences of any problematic results. For example, in Figure 5, the output of PE A1.3 normally flows to B1.1. But what if A1.3 has a problem and cannot produce the normal result? What will happen if it discovers a flaw in earlier work? Suppose that the effect of such a failure in the process would be to go back and rework A1.1, in which case the PE owner adds another (conditional) output deliverable (with A1.1 as its receiver) to represent the undesired rework path. A single PE may have multiple failure modes, depending on the type of problem it encounters. See [Eppinger and Browning, 2012] for a discussion of FMEA in the microprocessor design process at Intel. Modelers may capture PE failure modes explicitly in the attribute, “Potential Traps and Failure Modes” (Table 4).

4.4 Master and Shadow PEs

As mentioned in Heuristic 16 (section 3.5), some PEs occur in several places in the PD process—not even counting iterations, rework, or multiple modes. For example, each of several design areas may have PEs such as “Manage configuration” or “Manage risk.” Initially, different PE owners and their designees will define each of these PEs separately. Later, however, the CMT may scan the overall process architecture to identify similar PEs as candidates for some amount of more centralized management.

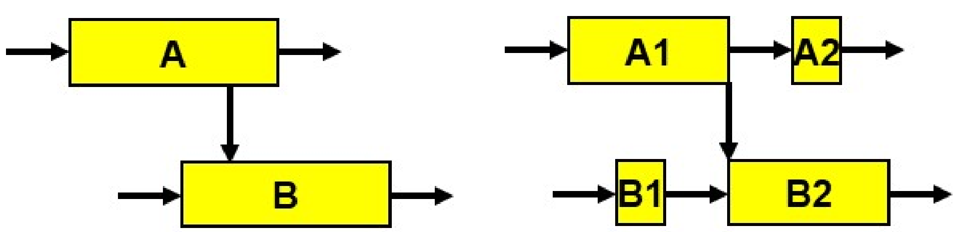
A master PE provides the baseline description for all other (shadow) instances of the PE. It includes reference(s) to any shadow PEs. Only one master PE may exist, although it may have several modes. Whereas modes distinguish versions of a PE at a particular location in the process architecture, a shadow PE resides in a *separate location* in the process architecture. A shadow PE inherits the attributes of the master PE by default, only capturing the differences from the master PE (e.g., different suppliers and consumers). A shadow PE may have its own modes. Multiple PEs may shadow one master. Whenever a master or one of its shadow PEs changes, it should trigger a review to see if the changes should propagate to each. For instance, if a shadow proposes a change, the change might also apply to the master and any other shadows. The owners of the master and shadow PEs should jointly approve all exceptions and changes.

4.5 Overlapping Activities

Natural overlapping (or concurrency) occurs when two or more *independent* PEs work concurrently; *artificial overlapping* occurs when two or more *dependent* or *interdependent* PEs do so. This subsection addresses how to deal with both in the model.

So far, we have assumed that deliverables are not available until the completion of its supplying PE, and that a PE must have all of its input deliverables to start work. Although such assumptions should not be problematic at lower levels of the model, at higher levels they are too constraining. A PE may not require some inputs until after its start time, and it may produce some outputs prior to its finish time. Many of these situations fall into the category of natural overlapping, which modelers may handle by adjusting PE Inputs and Outputs and deliverable Availability. Where needed, add a sub-attribute to each PE Input, "When Needed"—the time when the deliverable is needed by the PE, expressed as a percentage of the PE's completion (e.g., 0% indicates an input needed to begin the PE, whereas 50% indicates an input needed only for the second half of the PE). Set all PE Input "When Needed" attributes to 0% by default. Also where needed, add a sub-attribute to each PE output, "When Ready"—the time when each output is ready, expressed as a percentage of the PE completed (e.g., 50% indicates an output available after the first half of the PE, whereas 100% indicates an output available only when the PE is finished). All PE Output "When Ready" attributes set to 100% by default. Finally, update PE EST, LST, EFT, and LFT measures and deliverable Availabilities accordingly (a good IPM software tool would do this automatically).

Multilevel modeling greatly helps to address such situations. Just because two PEs overlap at one level does not imply that all of their children PEs need do so. For example, see Figure 6 and suppose two PEs, A and B, overlap because A provides a deliverable to B when A is 80% complete and B is 20% complete. Suppose we decompose each PE into two parts, prior and subsequent to this deliverable. Then, A1 provides to A2 and B2, but not to B1; B2 depends on A1 and B1, but not A2; artificial overlapping becomes natural instead. Another example in [Browning, 2002] shows three overlapping PEs whose children may be executed largely sequentially, demonstrating that decomposition provides a general and preferred way to handle many situations of overlapping. Modelers may parse deliverables as well as PEs where helpful.



(a) Artificial overlapping (b) Natural overlapping

Figure 6: Changing artificial to natural overlapping ones through further decomposition

4.6 Proceeding "At Risk"

In cases of purely informational inputs (which, in a PD process, is most of them), a PE may often begin without all of its inputs by making assumptions instead—a degree of freedom that may be helpful or problematic depending on the situation [Denker et al., 2001; Loch and Terwiesch, 2005]. Starting with assumptions in lieu of actual inputs causes artificial overlapping, potential rework, and thus risk [Browning and Eppinger, 2002; Meier et al., 2015]. In a descriptive model, it is important to identify situations where assumptions may serve as proxies, as evinced by dependent PEs proceeding before the actual availabilities of their input deliverables. Such situations may account for some of the discrepancies between the reported process and historical data about actual PE start and stop times.

One way to model these effects is to capture an estimate of how easy or difficult it is to make a good assumption in each case. Modelers should consider factors such as the strength of the PE's dependency on the input, the difficulty of estimating the input's characteristics, and the typical likelihood of the input to change over time in the PD project [Austin et al., 1996]. As any of these factors increase, so will the risk of proceeding based on an assumption in lieu of the official input. Comparing the resulting tradeoffs requires advanced techniques [Browning and Eppinger, 2002; Meier et al., 2015], but this can be saved for later. For now, add a further description to each of a PE's Inputs, noting its probability of causing rework if assumed prematurely.

4.7 Additional PE and Deliverable Attributes

Modelers may also enlist other attributes of PEs and deliverables from Table 1. See the guidance in Table 4 and Table 5. Modelers may choose to add these attributes later, after establishing the base model. We already mentioned some of these attributes earlier. The footnotes to Tables 2-3 and 4-5 indicate that the IPMIS will actually capture PE or deliverable System Identification Numbers (SIDs). That is, rather than listing the names of these objects as the attributes of other objects, the attributes will simply contain the other objects' unique (SIDs), which act as pointers to those objects. When the names change, the SIDs will continue to provide stable links among the objects. The IPM software tool would replace the SIDs with the latest PE and deliverable names for viewing purposes.

4.8 Formalizing Other Project Domains with Additional Modeling Objects

PEs and deliverables form the essential foundation of a process model, and these objects' attributes link them to other project domains such as the product/result, organization, tool, and requirement/goal subsystems [Browning et al., 2006]. However, modelers may want to formalize objects in these other domains, in which case modelers would replace their names in the PE and deliverable attributes with pointers/links to these objects. Figure 1 shows a few examples, and Table 6 suggests attributes for each of seven additional objects (still more could be added). Extending the model in this way makes it much more than a basic process model and more of a multidomain, *project architecture* model [Eppinger and Browning, 2012]. However, the process model provides a solid foundation for managing "organizational knowledge" about what, how, and when work is done—a foundation upon which many other aspects of a project may build.

Table 4: Guidance for some additional attributes of PEs (most described in [Browning, 2009])

Model Status	Set to "Under construction," "Under negotiation," "Approved," etc.
Exit Criteria	Make a bulleted list of the events *and* conditions that should exist for the PE to finish. These could include specification of the required maturity level of outputs and/or conditions for routing outputs to one receiver or another.
Verification Steps	Make a bulleted list of the steps that ensure the outputs meet required quality or performance criteria. If there are many, it may make sense to define a child PE focused on verification. This attribute may be unnecessary if already addressed adequately in the Exit Criteria.
Master/Shadow PE(s)[a]	For a Master PE, this attribute lists any other PEs that shadow it. For a Shadow PE, this attribute lists the Master PE.
Training/Skills	For each Role, make a bulleted list of the required skills and training (e.g., certifications) for this PE.
Potential Traps and Failure Modes	Make a bulleted list of the ways that PE or its outputs can run into cost, schedule, resource, or performance problems. These could include risk drivers and/or "lessons learned." Focus on the less-obvious pitfalls; capture information from the experience and knowledge of the workforce; include information that will prevent future problems and surprises; make future workers aware of the things that tend to go wrong. Also, include any advice on mitigation and recovery plans.
Opportunities for Improvement	Note opportunities for future improvements to this PE and/or its input/output deliverables. These could include new methods, tools, technologies, tests, etc. If an improvement applies specifically to a particular part of the PE, consider listing it in a child PE instead.
System Identification Number (SID)	A unique, distinguishing, object identification number, ideally assigned automatically by the IPMIS; should follow conventions such as those in the ISO/IEC 81346 standard series (http://www.81346.com/) [Balslev, 2014]

[a]PE names to be replaced with SIDs in the IPMIS

Table 5: Guidance for some additional attributes of deliverables (most described in [Browning, 2009])

Model Status	Set to "Under construction," "Under negotiation," "Approved," etc.
Parent[b]	Name of the parent deliverable, if applicable; otherwise "n/a"
Children[b]	Names of any children deliverables, if any; otherwise "n/a"
System Identification Number (SID)	A unique, distinguishing object identification number, ideally assigned automatically by the IPMIS; should follow conventions such as those in the ISO/IEC 81346 standard series (http://www.81346.com/) [Balslev, 2014]

[b]Deliverable names to be replaced with SIDs in the IPMIS

Table 6: Examples of additional modeling objects and attributes

Organizational Unit	User/Individual	Tool	Issue	Resource	Goal	Product Component
• Name • SID • Owner (person) • Parent • Constituents • Assignments (PEs) • Level • Measures (Size, etc.) • Resources	• Name • SID • Contact info. • Privileges • Password • Clearance • Skills • Roles (available) • Tools (certified) • Membership (org. unit) • Assignments (PEs) • Measures (Workload, etc.) • Resources controlled	• Name • Version • SID • Owner • Certification	• Name • SID • Owner • Originator • Affected objects (PEs, deliverables, etc.) • Related issues • Status • Time stamp • Comments • Disposition	• Name • SID • Owner • Assigned PEs (with Amount) • Measures (Capacity, etc.) • Related resources	• Name • SID • Owner • Parent • Constituents • Assigned PEs • Assigned Deliverables • Measures (Weighting, Risk, etc.)	• Name • SID • Owner (of design) • Parent • Constituents • Defined by (PEs, deliverables) • Inputs (source, type, strength, etc.) • Outputs (sink, type, strength, etc.)

5. Choosing Software Tools to Support IPM

As should be apparent from the previous sections, appropriate software tools are imperative for successful IPM. The vast number of interlinked PEs and deliverables, with their many attributes, simply cannot be handled with paper [Steiner, 1998; Pohlmann, 2002] or electronic documents, spreadsheets, slides, or drawing tools. Although each of these can be helpful at times—even to a point where they may be a deceptively compelling starter tool for modelers—their insufficient capabilities have caused many process modeling efforts to stall or fail to deliver long-term value. A lack of appropriate tools is one of the largest barriers to successful IPM. This paper does not strive to provide a comprehensive description or set of requirements for the ideal software tool, despite mentioning several requisite functions and capabilities. However, this section will offer a few comments on appropriate tools.

We must distinguish between the IPMIS, a database for storing the vast PD process model, from what we have referred to as the "IPM software tool," which provides capabilities for entering, integrating, visualizing, and verifying the process model (Figure 7). Most commercially available tools for process modeling combine these two systems, which is fine as long as the database is open to other means of access. It is possible to have more than one IPM software tool, if desired by various user groups. Moreover, it is highly desirable to support other available display and modification portals or *views* [Browning, 2009, 2010, 2013]. The IPMIS database provides the "common denominator" [Curtis et al., 1992], the common well from which all other views draw. It meshes with enterprise standards such as service-oriented architecture (SOA) and Federated Enterprise Reference Architecture (FERA). The IPM software tool, on the other hand, is the primary tool for IPMIS input and output. It requires capabilities such as easy navigation and searching, multiple views, configuration management, change management, version control, access security, automation (input, output, integrity), import/export from/to other enterprise information systems [e.g., Romero and Vernadat, 2016], and permissions management (read, write/change/delete) for various roles (e.g., PE owners, their designated modelers, reviewers, approvers, CMT, auditors, etc.). Other display and modification portals may include internal web sites and various tools for product models, workflow, product data management (PDM), enterprise resource planning (ERP), project management, etc.

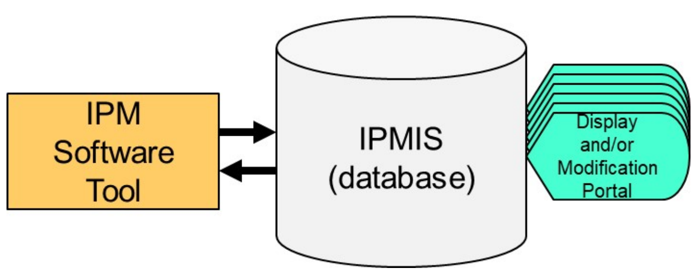


Figure 7: Distinction between the IPM software tool and information system and other various access tools

IPM directs enterprises to build rich models of how to integrate the work of hundreds or thousands of agents to develop complex products. Such information represents thousands of years of work experience and lessons learned—organizational "knowledge" about some of the most impactful aspects of PD. Its enormous value cannot be overstated. Once digitized, it becomes even more valuable to the enterprise as a basis for better planning, management, further learning, and continuous improvement. It also becomes easier to steal. Hence, it is imperative that the IPM software tool, IPMIS, and any other viewing tools have strong access control and other security safeguards, as befitting a business-critical technology. However, information protection must be balanced with usability: users must be able to find and get what they need quickly and easily, and model changes must be fast and simple.

6. Guiding and Managing the IPM Project

Once initially completed, the process model will be maintained indefinitely within the enterprise as part of normal operations. However, reaching that point of initial completion requires an appropriately managed project. Process modeling endeavors are prompted by a particular urge, so it makes sense to understand well the stakeholders, their preferences, the business case, the available resources, requirements, objectives, purposes, etc.—the conventional ingredients for chartering the IPM project. The IPM project must be well planned, in terms of activities, resources, responsibilities, schedules, milestones, reviews, etc. Managers may use agile practices, such as organizing the IPM steps into sprints. Expert resources must be available to adjudicate technical issues, such as depth of decomposition. The IPM project should include implementation activities such as training various users and serving as the new basis for proposal preparation and project planning. Of course, it is essential to report status, advertise the results and value added by project, and manage stakeholder expectations. Key status elements may include model levels completed, PEs defined, interfaces confirmed (integration status), etc.

Francis Bacon famously stated that knowledge is power. Anytime an enterprise seeks to gather tacit knowledge from its workforce, some power shifts. Workers fear that their knowledge is the only thing that makes them valuable to the organization. That is a separate debate, yet the IPM project must anticipate the likelihood that not everyone will cheerfully comply with its endeavors. Political capital will also be necessary to drive interface negotiations and ensure the IPM work occurs along with so-called “real” work. Seek allies among groups that benefit from the integration of disparate knowledge, such as systems engineers, functional “home” organizations, the project management office (PMO), and executives. As soon as possible, enterprise leadership must clearly demonstrate its commitment to the IPM work and communicate the message that it is not just the IPM project’s job but, henceforth, an ongoing part of everyone’s job, a new way of doing business. The IPM project must provide some value quickly—e.g., by giving people enhanced connectivity along the critical, problematic information flow paths in PD projects.

7. Conclusion

Developing complex products requires enormous amounts of skills, and vast amounts of foresight and experience make the process as efficient and effective as possible. People with the right knowledge are hard to come by, as they retire or leave an enterprise for other opportunities. It is possible to capture and manage much more of this knowledge using advanced techniques for IPM. Although PD is never performed exactly the same way twice, most design activities are consistent [Austin et al., 2000; Louis-Sidney et al., 2016] and may be reused [Davies et al., 2009] across projects. Despite the appeal of agile approaches in many situations, it is wasteful and dangerous to “muddle through” and “reinvent the wheel” on each PD project. Increased process standardization can increase value [Browning, 2014] and even improve innovation [Mir et al., 2016]. PEs are building blocks for the rapid construction of agile processes with prequalified deliverables [Gonzalez-Perez and Henderson-Sellers, 2008]; they can enable (rather than impede) fast change and the absorption of better practices.

A previous paper [Browning et al., 2006] laid out key motivations and considerations for PD process modeling. This paper has followed with detailed guidance for building integrated models that capture and help manage PD process information. Approaches used for more repetitive business processes are informative but insufficient to this purpose. Users seek support from process models for various purposes, use cases, or concerns. Browning [2009] identified and described 28 such purposes (column one of Table 1) across five user groups (process owners; project planners and schedulers; project managers and team leaders; engineers, designers, and other team members; and process auditors, assessors, and appraisers). Although IPM can lead to a process model that addresses any of these purposes, it has a *knowledge management* (technically, information management) emphasis, accentuating model richness, effectiveness, versatility, and reusability over sheer model-building efficiency. IPM leads to an integrated, object-oriented, distributed, flexible, and dynamic model. It helps establish alignment and accountability throughout the organization. Each PE is a gene in the PD process genome, the essential code describing what work is done, with what effort, when, and how it connects to other work to culminate in a product recipe. Its integrated nature supports improved managerial decision making from a systems perspective. Developing and maintaining this information, in a way that serves all of its users, provides a source of competitive advantage. The PD process model is the nexus of the people and tools that together provide an enterprise with the capability [Henderson-Sellers and Ralyté, 2010] to develop products. Its formulation and ongoing improvement is worthy of the full-time attention of a group in the core organization.

With its focus on IPM, this paper says little explicitly about how to *use* the resulting model. That is a topic for future work, whose topics include process-model-based management; rapid project planning and estimation (scheduling, budgeting, resource loading, staffing, etc.); process analysis, roadmapping, standardization, tailoring, scaling, and improvement; and process model improvement.

8. References

R. Aguilar-Savén, Business Process Modelling: Review and Framework, Int J of Prod Econ 90 (2004), 129-149.

S. Austin, A. Baldwin, and A. Newton, A Data Flow Model to Plan and Manage the Building Design Process, Journal of Engineering Design 7 (1996), 3-25.

S. Austin, A. Baldwin, B. Li, and P. Waskett, Integrating Design in the Project Process, Proceedings of the ICE: Civil Engineering 138 (2000), 177-182.

T. Bahill, R. Botta, E. Smith, What Are Levels?, 15th Annual Int Symp of INCOSE, Rochester, NY, Jul 10-14, 2005.

H. Balslev, Reference Designation System for Coding System Objects, INCOSE Insight 17 (2014), 28-30.

T. Black, C. Fine, and E. Sachs, "A Method for Systems Design Using Precedence Relationships: An Application to Automotive Brake Systems," MIT Sloan School of Management, Working Paper no.3208, Cambridge, MA, 1990.

C. Bock, SysML and UML 2 Support for Activity Modeling, Systems Engineering 9 (2006), 160-186.

R.E. Bohn, Measuring and Managing Technological Knowledge, Sloan Management Review 36 (1994), 61-73.

T.R. Browning, Process Integration Using the Design Structure Matrix, Systems Engineering 5 (2002), 180-193.

T.R. Browning, and S.D. Eppinger, Modeling Impacts of Process Architecture on Cost and Schedule Risk in Product Development, IEEE Transactions on Engineering Management 49 (2002), 428-442.

T.R. Browning, On Customer Value and Improvement in Product Development Processes, Sys Eng 6 (2003), 49-61.

T.R. Browning, E. Fricke, and H. Negele, Key Concepts in Modeling Product Development Processes, Systems Engineering 9 (2006), 104-128.

T.R. Browning, and R.V. Ramasesh, A Survey of Activity Network-Based Process Models for Managing Product Development Projects, Production & Operations Management 16 (2007), 217-240.

T.R. Browning, The Many Views of a Process: Towards a Process Architecture Framework for Product Development Processes, Systems Engineering 12 (2009), 69-90.

T.R. Browning, On the Alignment of the Purposes and Views of Process Models in Project Management, Journal of Operations Management 28 (2010), 316-332.

T.R. Browning, Managing Complex Project Process Models with a Process Architecture Framework, International Journal of Project Management 32 (2013), 229-241.

T.R. Browning, A Role-Playing Game for Teaching about Enterprise Process Integration, Journal of Enterprise Transformation 4 (2014), 226-250.

T.R. Browning, Program Agility and Adaptability, INCOSE Insight 17 (2014), 18-22.

P.-J. Courtois, On Time and Space Decomposition of Complex Structures, Communications of the Association for Computing Machinery 28 (1985), 590-603.

B. Curtis, M.I. Kellner, and J. Over, Process Modeling, Communications of the ACM 35 (1992), 75-90.

A. Danner-Schröder, and D. Geiger, Unravelling the Motor of Patterning Work: Toward an Understanding of the Microlevel Dynamics of Standardization and Flexibility, Organization Science 27 (2016), 633-658.

A. Davies, D. Gann, and T. Douglas, Innovation in Megaprojects: Systems Integration at London Heathrow Terminal 5, California Management Review 51 (2009), 101-126.

S. Denker, D.V. Steward, and T.R. Browning, Planning Concurrency and Managing Iteration in Projects, Project Management Journal 32 (2001), 31-38.

D. Dori, *Object Process Methodology*, Springer, New York, 2002.

P. Drucker, *Post-Capitalist Society*, Harper Business, New York, 1993.

C. Eckert, Generic and Specific Process Models: Lessons From Modelling the Knitwear Design Process, Tools and Methods of Competitive Engineering (TMCE) Conference, Ljubljana, Slovenia, Apr 18-22, 2006.

S. Eppinger, and T. Browning, *Design Structure Matrix Methods and Applications*, MIT Press, Cambridge, MA, 2012.

K. Forsberg, H. Mooz, and H. Cotterman, *Visualizing Project Management*, Wiley, Hoboken, NJ, 2005.

S. Friedenthal, A. Moore, F. Steiner, *A Practical Guide to SysML*, Elsevier/Morgan Kaufmann, Waltham, MA, 2014.

C. Gonzalez-Perez, and B. Henderson-Sellers, A Work Product Pool Approach to Methodology Specification and Enactment, Journal of Systems and Software 81 (2008), 1288-1305.

M. Halpern, Cracking Complexity in Project Management, Computer-Aided Engineering 18 (1999), 56-57.

M. Hammer, Seven Insights About Processes, conference The Strategic Power of Process: From Ensuring Survival to Creating Competitive Advantage, Boston, Mar. 5-6, 2001.

B. Henderson-Sellers, and J. Ralyté, Situational Method Engineering: State-of-the-Art Review, Journal of Universal Computer Science 16 (2010), 424-478.

J. Hess, C. Reuter, V. Pipek, and V. Wulff, Supporting End-User Articulations in Evolving Business Processes: A Case Study to Explore Intuitive Notations and Interaction Designs, Int J of Cooperative Information Systems 21 (2012), 263-296.

P.A. Howard, Deliverable-Oriented Project Management, Project World '98, 1998.

D.W. Hubbard, *The Failure of Risk Management*, Wiley, New York, NY, 2009.

M. Klun, P. Trkman, Business Process Management - At the Crossroads, Business Process Management J 24 (2017).

M. La Rosa, M. Dumas, A.H.M. ter Hofstede, and J. Mendling, Configurable Multi-perspective Business Process Models, Information Systems 36 (2011), 313-340.

V. Lévárdy, and T.R. Browning, An Adaptive Process Model to Support Product Development Project Management, IEEE Transactions on Engineering Management 56 (2009), 600-620.
C.H. Loch, and C. Terwiesch, Rush and Be Wrong or Wait and Be Late? A Model of Information in Collaborative Processes, Production & Operations Management 14 (2005), 331-343.
L. Louis-Sidney, V. Cheutet, and S. Lamouri, Proposal for a Process Oriented Knowledge Management System (PKMS), International Journal of Product Development 21 (2016), 267-287.
H. Lykins, S. Rose, and P.C. Scott, An Information Model for Integrating Product Development Processes, 8th Annual International Symposium of INCOSE, Vancouver, BC, July 26-30, 1998.
T. Malone, K. Crowston, J. Lee, B. Pentland, C. Dellarocas, G. Wyner, J. Quimby, C. Osborn, A. Bernstein, G. Herman, M. Klein, and E. O'Donnell, Tools for Inventing Organizations: Toward a Handbook of Organizational Processes, Management Sci. 45 (1999), 425-443.
T. Malone, K. Crowston, and G. Herman (Eds.), *Organizing Business Knowledge*, MIT Press, Cambridge, MA, 2003.
O. Marjanovic, and R. Freeze, Knowledge-Intensive Business Process: Deriving a Sustainable Competitive Advantage through Business Process Management and Knowledge Management Integration, Knowledge & Process Management 19 (2012), 180-188.
B. Matthies, Process Capital: A Synthesis of Research and Future Prospects, Knowledge and Process Management 21 (2014), 91-102.
C. Meier, T.R. Browning, A.A. Yassine, and U. Walter, The Cost of Speed: Work Policies for Crashing and Overlapping in Product Development Projects, IEEE Trans on Engineering Management 62 (2015), 237-255.
J. Mendling, H.A. Reijers, and J. Recker, Activity Labeling in Process Modelling: Empirical Insights and Recommendations, Information Systems 35 (2010), 467-482.
M. Mir, M. Casadesús, and L. Petnji, The Impact of Standardized Innovation Management Systems on Innovation Capability and Business Performance: An Empirical Study, J of Eng and Tech Management 41 (2016), 26-44.
J. Murdoch, J.A. McDermid, and P. Wilkinson, Process Tailoring in Iterative Development, 11th Annual International Symposium of INCOSE, Melbourne, Australia, July 1-5, 2001.
H. Negele, E. Fricke, L. Schrepfer, and N. Härtlein, Modeling of Integrated Product Development Processes, 9th Annual International Symposium of INCOSE, Brighton, UK, June 6-11, 1999, pp. 1253-1261.
B. O’Donovan, T.R. Browning, C.M. Eckert, and P.J. Clarkson, "Design Planning and Modelling," in P.J. Clarkson, and C.M. Eckert (Eds.), *Design Process Improvement: A Review of Current Practice*, Springer, 2005, pp. 60-87.
G.A. Pall, *The Process-Centered Enterprise*, St. Lucie Press, New York, 1999.
J.H. Panchal, M.G. Fernandez, C.J.J. Paredis, J.K. Allen, and F. Mistree, A Modular Decision-centric Approach for Reusable Design Processes, Concurrent Engineering 17 (2009), 5-19.
H. Park, and M.R. Cutkosky, Framework for Modeling Dependencies in Collaborative Engineering Processes, Research in Engineering Design 11 (1999), 84-102.
K. Parris, Implementing Accountability [in Software Development], IEEE Software 13 (1996), 83-93.
L.D. Pohlmann, Web-based Process Documentation – Getting Over the “Paper Mentality” Hurdle, 12th Annual International Symposium of INCOSE, Las Vegas, NV, 2002.
R.V. Ramasesh, and T.R. Browning, A Conceptual Framework for Tackling Knowable Unknown Unknowns in Project Management, Journal of Operations Management 32 (2014), 190-204.
E. Rechtin, *Systems Architecting*, PTR Prentice Hall, Englewood Cliffs, NJ, 1991.
J. Recker, and J. Mendling, The State of the Art of Business Process Management Research as Published in the BPM Conference: Recommendations for Progressing the Field, Business Info Systems Engineering 58 (2016), 55-72.
D. Reinertsen, Lean Thinking Isn't So Simple, Electronic Design 47 (1999), 48.
D.G. Reinertsen, *Managing the Design Factory*, The Free Press, New York, 1997.
D. Romero, and F. Vernadat, Enterprise Information Systems State of the Art: Past, Present and Future Trends, Computers in Industry 79 (2016), 3-13.
A.L. Scherr, A New Approach to Business Processes, IBM Systems Journal 32 (1993), 80-98.
D. Shapiro, M.D. Curren, and P.J. Clarkson, DPCM: A Method for Modelling and Analysing Design Process Changes Based on the Applied Signposting Model, Journal of Engineering Design 27 (2016), 785-816.
H.A. Simon, *The Sciences of the Artificial*, MIT Press, Cambridge, MA, 1996.
D.M. Steiger, Enhancing User Understanding in a Decision Support System: A Theoretical Basis and Framework, Journal of Management Information Systems 15 (1998), 199-220.
R. Steiner, Process Management for Skeptics (or The Case for Process Management in Modern Naval System Development), 8th Annual International Symposium of INCOSE, Vancouver, BC, Jul. 26-30, 1998, pp. 897-900.
W.M.P. van der Aalst, Process Discovery: Capturing the Invisible, IEEE Computational Intelligence Magazine 5 (2010), 28-41.
D.C. Wynn, and P.J. Clarkson, Process Models in Design and Development, Research in Engineering Design (2017).