Let's truly add systems to industrial engineering

Standard reference models for ISE domains are necessary to propel curriculum, profession into the future

By Timothy Sprock and Leon F. McGinnis

Industrial engineering as a discipline has always been about building and using empirical or mathematical models to explain or prescribe systems. Frederick W. Taylor analyzed unit manufacturing processes and task management in the 1890s, culminating in the publication of *Shop Management* (1903) and *The Principles of Scientific Management* (1911). H.L. Gantt and others analyzed networked processes and project management (1910s). Walter A. Shewhart's control charts introduced statistical methods for process control (1920s). Operations research emerged as a discipline in the 1940s and became the rigorous, analytic foundation of industrial engineering in the 1950s and 1960s. This became a cornerstone of the curriculum with the publication of the "Roy Report" in 1967. (See sidebar on Page 31.) Digital computing in the 1960s made modeling methods more powerful and applicable. Ubiquitous computing emerged in the 1980s and put advanced modeling tools on every IE's desktop.

Today, industrial engineers work in many large, complex cyber-physical systems, such as semiconductor device manufacturing, aircraft production, global supply chains and healthcare delivery. IEs develop many kinds of analysis models in these application domains. The factor limiting the contribution or impact of IEs is not our analytical methods or computational tools. Rather, it is our ability to deal with complex interactions among a multitude of stakeholders and decision-makers, interactions that are difficult or impossible to capture in single-dimension analysis models. The institute's recent name change, adding "systems" to become the Institute of Industrial and Systems Engineers, reflects the evolution of IE to industrial and systems engineering (ISE).

Another engineering profession works in the systems domain. Systems engineering (SE) emerged as a discipline in the aerospace and defense industries to cope with similar problems in developing large, complex, multidisciplinary systems – missile systems, space missions, fighter aircraft, ships and submarines. Traditionally, SE has focused on system development process models to support its role as the coordinator, integrator and mediator among the many disciplines that contribute to the design of these systems. SE lifecycle models, such as the "vee," describe system design phases, from articulating stakeholder needs and concepts of operations (ConOps) through to integration, testing and deployment. SE coordination and integration processes manage development of system requirements and architecture, which historically have been captured as documents. But as systems have become larger and more complex, document-based processes have proven inadequate.

In response, representing systems with models rather than documents has become one of the modern foundations of systems engineering, an initiative known as model-based systems engineering (MBSE). System models describe requirements, functions, structure, behavior and properties of the system in the language of users, practitioners or stakeholders. Yet, they are independent of any specific engineering discipline, analysis language or analysis tool – explicitly analysis agnostic – and are constructed in standardized languages dedicated to system modeling, such as the OMG Systems Modeling Language (OMG SysML). Expressing models using analysis-agnostic but domain-specific language enables engagement of the stakeholders who have the expertise required to validate the system specification throughout the design process.

These analysis-agnostic and machine-readable system models constitute a "single source of truth" from which discipline- or subsystem-specific analysis models can be created, enabling engineers to study many aspects of system performance and behavior. In many cases, routine documentation and analysis models, such as summing weight or power consumption across multiple subsystems, can be generated automatically from the system specification, as JPL did for the completely model-based Europa mission. Also, because these analysis models conform to a common system specification, analyzing subsystem interactions becomes feasible using interoperable tools, such as simulations. The ability to analyze subsystem specifications continuously during the design process, especially in early phases, minimizes costly rework and redesign.

These kinds of system models also are foundational for "digital thread" implementations, including the creation of a "digital twin" for each product system. These digital models track a product's production and sustainment operations throughout its life cycle. Model-based methods are transforming systems engineering in industries as diverse as space exploration, aviation and automobiles.

Unlocking "systems" in ISE

Contemporary SE practice focuses on the product development life cycle, largely ignoring traditional industrial engineering concerns regarding production, distribution, deployment and sustainment of the product system life cycle.

However, as model-based systems engineering methods and "digital thread" implementations evolve and mature, the SE community is recognizing this gap. There is a growing awareness of the need to integrate production and logistics concerns with traditionally design-centric product life cycle decision-making. This presents a huge opportunity for ISE and SE to collaborate: ISE brings deep domain knowledge in manufacturing and supply chains, along with a legacy of superb analytical modeling of production and logistics systems; SE brings innovative methods and tools for system modeling. Such a collaboration would significantly enhance contemporary SE practice as well as introduce a new generation of systems methods and tools to ISE.

From the ISE perspective, such a collaboration not only opens new areas for practice and research, it brings much needed innovation to traditional ISE practice and research. Imagine, for example, that ISE practitioners with expertise in a domain like manufacturing could gain access to powerful tools, such as queuing analysis or discrete event simulation, to answer routine questions simply by creating explicit system models using domain-specific system modeling tools. Or imagine that domain-specific system design methods for designing warehouses, for example, were supported by integrated computational tools for system modeling and analysis. Based on the experience of SE, a model-based, systems approach for ISE (MBISE) is both conceptually and practically feasible, and the path toward that goal is reasonably clear. ISE needs to develop three key IE domain-specific elements: reference models, system design methodologies and integrated analysis tools.

Domain-specific reference models

ISEs are experienced in using modeling tools, from databases to spreadsheets to simulation to optimization. That experience teaches us that it is very easy to use powerful modeling tools to create ad hoc models that are difficult to maintain or reuse. How can ISE practitioners avoid that problem in creating system models?

The SE experience of MBSE teaches us that it is essential to first develop a way of thinking and talking about the system domain of interest – now being referred to as "reference model." Reference models provide the semantics and syntax for describing large classes of systems in the domain of interest and are used as a starting point for developing models of individual systems. In modern interoperable computing environments, these models incorporate many viewpoints, including descriptions of the hardware, control software, information technology systems – possibly even analysis models that provide decision support. Reference models supporting these viewpoints may be captured as libraries of validated, reusable model components and patterns for assembling them into meaningful systems, enabling system modelers to produce consistent results.

Separate reference models should be created for major subdomains of ISE, such as warehouses, transportation systems, manufacturing plants, supply chains and hospitals and healthcare delivery systems. For example, a reference model for warehousing would include detailed descriptions of the classes of objects in the systems, such as products (e.g., SKUs, pallets, cases, etc.), processes (e.g., pick, sort, pack), resources (operators, lift trucks, floor space, etc.) and facilities (departments, layouts, etc.). These classes can be combined to create reusable subsystem models, such as automated storage and retrieval systems or conveyor systems. These definitions address not only the class properties, but also interfaces, so that models can be checked to ensure valid connections between classes.

Domain-specific reference models also enable the development of complementary standard "testbeds." There are interesting questions that cannot be explored today because of the cost to develop high-fidelity simulation testbeds. These analysis models are time-consuming to develop, share and maintain using contemporary approaches. However, MBISE methods could make it possible to describe a system and its operating conditions and then automate the generation of the simulation testbed, complete with controllers that use standard interfaces for decision support. In this scenario, prospective researchers could focus on developing and benchmarking decision support methods, rather than developing the testbed itself.

Domain-specific design methodologies

Reference models for ISE-specific domains of practice are a critical first step. To apply reference models in a consistent, repeatable manner, there needs to be a corresponding system design methodology addressing the complete system life cycle. In the SE discipline, the methodology has several clearly identified phases: articulating stakeholder needs, identifying system requirements, developing logical system architectures, detailed subsystem design, implementation, integration, testing, validation and verification, and deployment. For each phase, there is a robust literature discussing methods, tools and practices.

Warehousing is an important domain of ISE research and practice. Warehouses can be argued to be simpler and easier to understand than, say, aircraft assembly, semiconductor manufacturing or global supply chains. Yet if one examines the ISE literature on warehousing or the textbooks that address warehousing, one will not find the kind of detailed, step-by-step design methodology that is common in other engineering disciplines. In fact, ISE research and teaching tends to approach design as an exercise in generating and evaluating alternatives, without much guidance for how those alternatives are generated. Adopting domain-specific design methodologies could facilitate a rich environment for exploring the theory of decision-making for multiple decision-makers across multiple system disciplines. MBISE will be most successful if a more rigorous approach to design is taken, and this represents a challenge to both our research and teaching missions.

Integrated analysis tools

A major benefit of MBISE approaches would be providing system modelers and designers with "push button" access to analysis models. In model-based system-analysis integration methods, decision support analysis models are derived, transformed or otherwise automatically generated from the analysis-agnostic system model. Multiple types of analysis models can be constructed from the same description of the system. Formulating routine analysis models to answer standard questions will no longer be an art practiced by the system modeler or designer, but rather a repeatable, deterministic activity with predictable outcome: high-quality, verifiable answers to those routine questions.

This runs counter to the traditions of ISE (and operations research), which emphasizes building analysis models. However, if we have useful reference models and common design methodology, then we can identify "standard" questions that can be answered with "standard" analyses. As an example, suppose the question is, "How should a pallet rack system be configured in terms of tier height, number and length of aisles to achieve a particular storage capacity?" We know how to answer this question, and developing a standard solution is possible, provided we have standard information models.

As ISE domain-specific tools for system design, planning and control become available and prove the value of standardized descriptions, we may see systems-related specializations within the discipline. For example, ISE systems designers may need to know which tools to use and when, while ISE systems analyzers may be the providers of specialized decision support. In the SE space, MBSE innovations have been driven by practitioners, often in collaboration with researchers. This is a good model for the ISE community. Without usable domain-specific tools, MBSE would have remained a concept and not a practice.

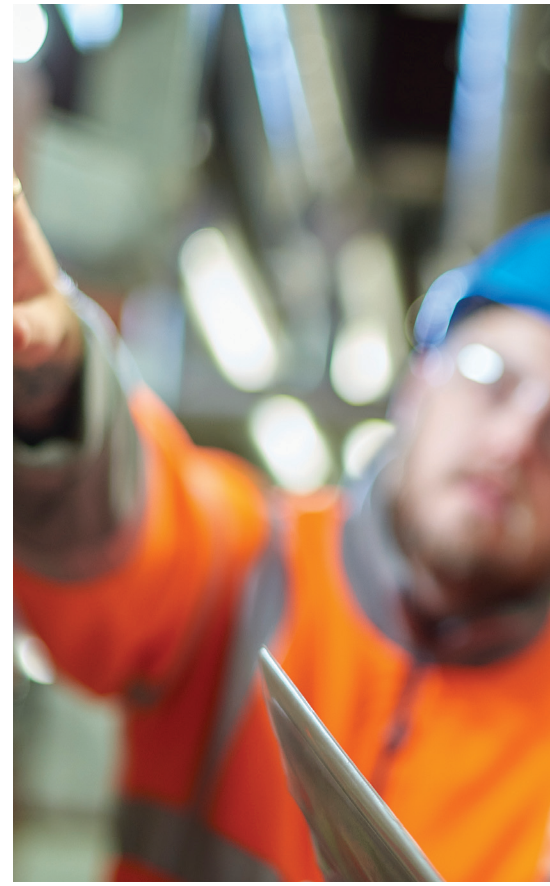
Preparing our profession for this future of I(S)E

Development of reference models, design methods and integrated analyses is necessary but not sufficient for the ISE profession to realize the benefits of MBSE. These new methods and tools must find their way into teaching, research and practice. This will require new teaching approaches that integrate systems thinking and design methodologies into the curriculum, as well as new approaches to formulating analysis models.

Incorporating a "systems" perspective in the curriculum requires a more holistic approach than the current practice of distinct courses addressing each analysis discipline (optimization, queuing, simulation) or subsystem (production, warehousing, logistics, inventory). A systems approach requires developing a deeper understanding of and methods for managing system complexity; a need that becomes apparent when multiple disciplines and multiple decision-makers are considered. This requires a shift toward describing systems as they are, including context and environment, their behavior and flows and their relationships and interactions between system components. These descriptions can be captured through formal systems modeling, a topic not currently found in the ISE curriculum.

In fact, in a future when so many routine analyses can be created automatically, systems modeling may be more important in the curriculum than analysis modeling. The knowledge and skill for building new analysis models may become the purview of a relatively small fraction of ISE professionals. We may need to confront questions such as: "Is there a difference between learning to be 'users' of analysis models and learning to be 'inventors' of analysis models? And does everyone have to be an analysis model inventor?"

Systems design is almost an unexplored territory for ISE researchers. Designing and teaching methods for selecting and optimizing individual components or subsystems is only one step of the design process. The larger challenge is to address decisions that cross component or subsystem boundaries. The curriculum needs to address other



aspects of the system life cycle, spanning the design process itself through the system's operation, sustainment and retirement. In teaching, we need to ensure that students understand that system design often involves messy trade-offs and the evaluation of incomplete problem definitions in a decision space that is not amenable to exact optimization methods. Students should appreciate that while we can focus on individual system components and construct analysis models to study simplified behaviors to gain insight into more complex behaviors of the real system, this approach only works if accompanied by methods for translating that insight into solutions to the original problem.

The challenge

The ISE community can provide leadership in the design and decision-making required to support the scale, complexity and degree of automation expected of modern ISE systems, but only by adapting our legacy knowl-

ISE curriculum: A legacy of the 1960s?

The legacy of Frederick W. Taylor and others defined the IE curriculum of the 1950s, when industrial engineers were seen as "efficiency experts" whose goal was to wring costs out of labor-intensive operations through work measurement, work methods, plant layout and simple engineering economic analysis.

Recognizing the critical need to transform the discipline into one that was "scientifically rigorous," a study was commissioned with support from the National Science Foundation and the endorsement of the American Society for Engineering Education to examine how the industrial engineering curriculum could respond to this new challenge.

The result was the "Roy Report," published in the September 1967 *Journal of Industrial Engineering*, the predecessor of *ISE* magazine and *IISE Transactions*. The report contained conclusions reached by a team of academics and practitioners led by Rob Roy, dean of engineering science of Johns Hopkins University, who conducted an intensive survey and debate about the future of IE. The report made the case that the "scientific and mathematical" foundation for IE should include the study of probability and statistics, stochastic processes and optimization.

The Roy Report provided the energy and direction for major curriculum revisions for the next decade, and the use of "operational research" methods quickly became ubiquitous in industrial engineering. It could be argued that the industrial and systems engineering curriculum today still reflects the recommendations of the Roy Report.

edge and tools to the required systems perspective. MBSE is one potential path for that adaptation. The MBSE approach to a collaborative ISE future starts with discipline-wide agreement on how to define our systems. Constructing standard reference models requires searching for and institutionalizing reusable, unambiguous "patterns" of system modeling.

An ISE discipline built on a foundation of standards-based, domain-specific reference models is one way to bring our legacy knowledge and tools into the systems arena. It enables two-way collaboration between stakeholders (industry) and solution providers (academics and software vendors). Collaborative platforms for sharing data in a consistent, predictable, usable format (standard schema and semantics) and for solutions conforming to the standard will enable contributions to be interoperable and easily deployed into production environments. Lessons learned in research could be validated on real data and quickly translated into deployable, commercial solutions. The research community must develop new methods and tools in the context of MBISE. Finally, tool vendors must produce a new generation of modeling and analysis tools for practitioners.

Other engineering disciplines sense the available opportunities to design smart production and logistics systems. Do industrial and systems engineers see themselves as system designers, implementers and optimizers, or analytics providers?

Answering this question about our role relative to "product systems" engineers requires an open discussion about the future of our profession and how we'll get there. ❖

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