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HISTORY AND PERSPECTIVE OF SIMULATION IN MANUFACTURING

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ABSTRACT

Manufacturing systems incorporate many semi-independent, yet strongly interacting processes, usually exhibiting some stochastic behavior. As a consequence, overall system behavior, in the long run but also in the short run, is very difficult to predict. Not surprisingly, both practitioners and academics recognized in the 1950's the potential value of discrete event simulation technology in supporting manufacturing system decision-making. This short history is one perspective on the development and evolution of discrete event simulation technology and applications, specifically focusing on manufacturing applications. This assessment is based on an examination of the literature, our own experiences, and interviews with leading practitioners. History is interesting, but it's useful only if it helps us see a way forward, so we offer some opinions on the state of the research and practice of simulation in manufacturing, and the opportunities to further advance the field.

1 INTRODUCTION

This invited contribution addresses the history of manufacturing simulation, specifically the research, development and application of discrete event simulation to answer interesting and important questions about manufacturing in general and/or about specific manufacturing scenarios. Clearly, a maximum of 15 pages is not adequate for a detailed account of every important contribution. Rather, we have attempted to paint a picture in broad strokes, attempting to see where we have come from in the past 60 years, and where we might be or should be going in the future. Our perspective is shaped, in part, by our combined 64 years of experience with using simulation in research and applications focused on manufacturing, and the more than 45 related dissertations that collectively we have supervised.

Our perspective is strictly that of "logistics", i.e., the flow of materials through the factory, and all the issues that arise in designing, planning and controlling that flow. These problems are frequently the focus of courses, research and applications of operations research in general, and discrete event simulation in particular. It must be noted that there are other important simulation applications in manufacturing, associated with processes and materials. For example, simulations are used to predict the performance of products prior to prototyping them, to predict performance of machine tools or robots prior to building them, and to predict the ergonomic stress associated with specific manufacturing operations. These are very interesting and important problems, but beyond the scope of the present effort.

We have approached this task from several different directions. Of course, we have looked at the literature, and what a vast literature it is. We give some indication of the size and scope of the literature, but make no claim to a comprehensive survey. We have discussed the evolution of simulation with leading practitioners in large companies and simulation software vendors, to try to understand their perspectives on how simulation has been used, and how the use has changed over the last fifty years. We provide a glimpse into our own experiences with simulation, as researchers and advisors to industry. Finally, we express some opinions, both about the evolution of manufacturing simulation, its current state and about its potential and future development. These are, of course, opinions, and our hope is to stimulate a lively discussion within the research and practice communities.

2 ABOUT MANUFACTURING

For readers who may not be familiar with manufacturing, we hope it is sufficient to say that “in manufacturing, material flows through processes, which are executed using resources, to change the material to a higher value state.” In this flow, material may be rejected and scrapped, or reworked, and it often has to wait for resources to become available. Manufacturing requires careful planning regarding resources, and the synchronization of a great many interacting processes.

Why is simulation such an attractive analysis tool for the manufacturing domain? It’s because simulation holds the promise of creating a “virtual factory” in which we can play out alternative decisions, strategies or policies, and see how they “actually” work. We can experiment, at low cost and no risk, on this virtual factory in ways that simply would not be possible in the real factory. To realize this promise, of course, requires a certain level of fidelity between the virtual and real worlds, and the ability to perform the required computations in acceptable time and cost. These are the three “pillars” of manufacturing simulation – fidelity, time, and cost.

The questions that we want to answer using simulation can vary widely, but fall into two general categories:

- What resources do we need? Here “resources” can be production materials, processing tools, fixtures, storage space, etc.
- How should we control the flow? Control implies decisions, which may address time-bucket oriented plans (intentions) or operational decisions about release, sequencing, assignment, routing or setup.

If we try to answer these kinds of questions from first principles, like conservation of flow or Little’s Law, we can get into trouble, because manufacturing systems are rarely ever in steady state. These two basic question types also indicate clearly what we must be able to describe in our “virtual factory” – the resources, the flows, and the controls – if we are to achieve a “high fidelity” representation of reality, and (we hope) get accurate predictions of the consequences of our decisions.

3 MANUFACTURING SIMULATION PUBLICATIONS

The application of discrete event simulation to manufacturing systems is a subset of the broader simulation application theme within the industrial engineering (IE), management science (MS), and operations research (OR) communities. Our emphasis has been on questions specific to manufacturing, including motivation, kinds of problems addressed, the role of simulation technology, and particularly, the interplay – or lack of it – between related research and applications. Although there are many methodological issues of interest, for the most part, those are left for others to discuss.

Five papers are important in setting the historical context. J.R. Jackson, of “Jackson network” fame, was among the first to employ digital computation to explore “job shop scheduling” problems. In Jackson (1957) a very simple model is described in which jobs have routes through processes, and transport times between machines are represented as a single random variable. Harling (1958) discusses related activities in the United Kingdom, focusing on technical issues of pseudorandom numbers and random variates, with a brief mention of a simple application. Conway, Johnson, and Maxwell (1958) describe the implementation of a “simulator” designed to investigate scheduling rules in a network of queues, with the “job shop” as the motivating example. A year later, Conway, Johnson, and Maxwell (1959) dive much deeper into the practical issues of implementing the simulator. Kuratani and Nelson (1960) report on the development of a job-shop simulator very similar to the Cornell Simulator and the design of initial experiments, although no experimental results are given.

Given the limitations of digital computers circa 1957, and the requirement to code using only low level computing abstractions, it is not surprising that the models explored at that time were so simplified. In fact, a very common observation by the authors at that time was that these computational models were highly abstracted, and that what was valuable from the computations were the insights, e.g., into what dispatching rules worked well, rather than tools for actually scheduling job shops. In these early papers, the authors recognized the limited fidelity, but were convinced that their models of structure and behavior were adequate for drawing broad conclusions about policies for controlling flow. This hints at an aspect of manufacturing simulation that remains important today – the challenge of using the available simulation modeling tools (languages) to capture, with sufficient fidelity, the important attributes of the manufacturing system.

3.1 Society for Modeling and Simulation International

The first issue of the journal *Simulation* was published in September, 1963. The earliest manufacturing application published is (Reitman 1967), who describes an application of the General Purpose Simulation System (GPSS) to model a semiconductor manufacturing system. Sims (1981) describes a GPSS model of a serial production line, and uses the model to determine what changes must be made to the process to achieve a desired throughput. Over the first 20 years of the journal (until 1983), these were the only manufacturing papers published.

The second 20 years of the journal saw a much greater interest in manufacturing-related simulation. Antonellli, Volz, and Mudge (1986) is an academic study using hierarchical and functional decomposition to model a robotic cell. This may be the first archival publication that suggests creating a reference model and automating the creation of much of the "tedious" code required to completely describe such a cell. Ford and Schroer (1987) is an academic study that uses natural language interpretation to automatically generate a SIMAN simulation of a printed circuit card assembly process. The overall approach is described, but there is little useful discussion of testing, validation or verification. Fan and Sackett (1988) is an academic study that describes the use of the logic programming language PROLOG to develop a simulator for flexible manufacturing system control. In another academic study, Ketcham, Shannon. and Hogg (1989) propose using a "network database structure" to maintain the information defining a manufacturing system, including state information. De Meter and Deisenroth (1991) present yet another academic attempt to develop a "modeling framework" that hints at object-orientation, but still fails to adequately integrate representation of structure with behavior and control. Kwon (1996) is motivated by the potential mismatch between the simulation model of a Computer-Integrated Manufacturing (CIM) system and the actual information system supporting the same CIM system. The proposed solution is to create an object model of the data sources, to somehow (using a "REFINER") "join" domain objects and simulation objects to form a "logical simulation model" and then a "GENERATOR" to create the actual simulation code. There are not many technical details and a reference to a fairly simple example, but the ideas are intriguing. Crawford, Percy-Robb, and Clark (1997) is focused on the problem of representing jobs that have complex "process plans". In (Piera et al. 2004), a simulation-optimization approach is described, where the simulation is via a colored Petri net (CPN). Because of the size of the CPN, only a very small example can be solved. A companion paper elaborates the approach with some AI techniques (Narciso, Piera, and Guasch 2010).

To better understand the industrial users, Mackulak, Chochran, and Savory (1994) surveyed 34 industrial organizations to identify the desirable features of a simulation platform. All the features identified in the survey were generic simulation features – there were no questions regarding the available modeling syntax or semantics. Does this reflect the interests of the practitioners or the perspective of the surveyor? Subsequently, Fowler and Rose (2004) identified "grand challenges" for modeling and simulation in manufacturing, which include (1) reducing problem solving cycles, (2) developing real-time simulation-based problem solving capability, and (3) true plug-and-play interoperability between simulation and other software tools. One aspect of reducing problem solving cycles is reducing the time required to create the simulation models.

In the second 20 years (1984-2004), there was more interest in manufacturing, but many of the published papers are somewhat conceptual, at least in the sense that no case study is presented. However, it seems clear there is a growing awareness of the “cost” of hand-coding simulation models, and an interest in finding ways to ameliorate this effort. The “grand challenges” are mostly about reducing the cost of simulation, but also recognize the opportunity to use simulation in a new way to support operational decision making.

Over the past decade (2005-2016), Simulation papers related to manufacturing have explored interesting applications, issues associated with applications, or novel approaches to using simulations. Moon, Kim, and Song (2005) is an application of simulation (Promodel) to support the design of a storage system for resequencing auto bodies prior to the finish coat paint booth. In (Robinson and Brooks 2010), a methodology for verification and validation is proposed and illustrated for an industrial application. Bouché and Zanni-Merk (2010) investigate the collection of data from a production line and methods for converting data into useful information about its performance. Xu, Moon, and Baek (2012) use simulation (Quest) to study alternative configurations for a transmission line and Analytic Hierarchy Process to guide selection under multiple criteria. The use of “digital humans” to study ergonomic issues is addressed in (del Rio Vilas, Longo, and Monteil 2012). A particular automotive paint shop is studied in (Dengiz and Belgin 2014), where an Arena model is used to construct a response surface with independent variables corresponding to numbers of quality control workers, number of final paint workstations and number of priming workstations.

In these papers, what we see is a growing interest in using simulation to support design decision making.

3.2 Other Journals

The number of manufacturing papers published in Simulation is small enough so that all at least could be examined for this history. However, when we turn to other outlets, the story is quite different. Table 1 below shows the growth in manufacturing simulation papers in the International Journal of Production Research (IJPR) – a well-regarded outlet for this kind of work – and in all journals abstracted by EBSCOhost (https://www.ebscohost.com/). By 2015, there were over 1600 manufacturing simulation papers in IJPR alone, and for all journals the number is more than 25,000. The rapid proliferation of manufacturing simulation publications after 1999 is an interesting phenomenon, to which we will return later. Figure 1 is a “word cloud” consisting of the 30 words most frequently found in the titles of the 1639 IJPR papers (and in some cases in the corresponding “key words”).

Table 1: Journal Publications by Decade

Decade	IJPR	All Jnls
1/60 - 12/69	9	90
1/70 - 12/79	26	213
1/80 - 12/89	112	615
1/90 - 12/99	284	1994
1/00 - 12/09	412	14244
1/10 - 12/15	796	26872

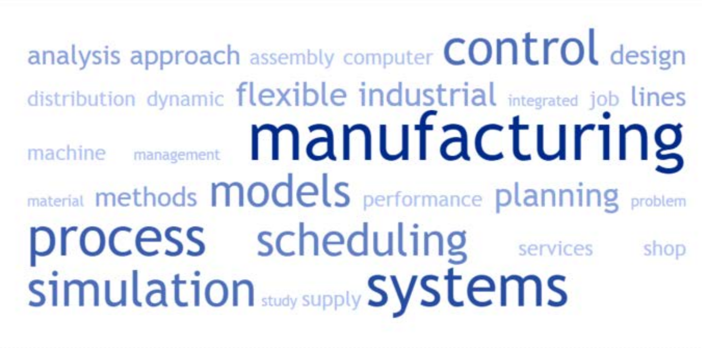

Figure 1: IJPR Title Words

3.3 Winter Simulation Conference

In the history of the Winter Simulation Conference, through 2016, there were 1448 papers addressing some aspect of manufacturing. A regression model of the number of publications per decade from the 70’s through the 2000’s has a near-perfect fit, with a growth rate of 153.6 papers per decade. Indications are, however, that the growth rate is slowing in the 2010’s. There are two interesting bibliometrics available for each paper published in the proceedings, the number of citations and the number of downloads. We’ve looked at these bibliometrics for the 1448 “manufacturing” identified papers.

There are 12 papers with more than 1000 downloads. By far the most frequently downloaded is a paper on the impact of radio-frequency identification (RFID) on supply chain dynamics (Young, Cheng, and Leung 2004). In fact, 5 of the 12 address (manufacturing) supply chains, including (Banks et al. 2002), (Gan et al. 2000), (Truong and Azadivar 2003), and (Vieira 2004). In order of number of downloads, the papers address: bee colony optimization for scheduling (Chong et al. 2006), animation of a fast food restaurant (Farahmand and Garza Martinez 1996), virtual reality for cooperative learning (Galvao, Martins and Gomes 2000), CIM enterprise modeling (Kateel, Kamath, and Pratt 1996), simulation based supply chain optimization (Truong and Azadivar 2003), introduction to SIMAN (Davis and Pegden 1987), distributed supply chain simulation (Gan et al. 2000), six sigma (McCarthy and Stauffer 2001), modeling supply chains with Arena (Vieira 2004), and a supply chain panel (Banks et al. 2002).

Similarly, there are 12 papers with more than 20 citations. In decreasing order of citation count, these papers address: simulation response surface models (Barton 1998), bee colony optimization of scheduling (Chong et al. 2006), a rollback algorithm for distributed simulation (Madisetti, Walrand, and Messerschmitt 1988), the Intelligent Manufacturing Systems MISSION architecture for distributed manufacturing (McLean and Riddick 2000), value of simulation in supply chains (Ingalls 1998), impact of RFID on supply chain dynamics (Young, Cheng, and Leung 2004), distributed supply chain simulation (Gan et al. 2000), visualization in manufacturing simulation (Rohrer 2000), sustainable manufacturing system design (Heilala et al. 2008), shifting bottleneck detection (Roser, Nakan, and Tanaka 2002), shop floor control (Smith et al. 1994), and simulation-based optimization (Law and McComas 2002). Interestingly, only 3 papers appear in both lists.

While it is risky to try to draw conclusions from such a small sample, it does seem obvious that manufacturing *qua* manufacturing did not generate the most interest. For these 21 papers, in fact, only five could be argued to be primarily about manufacturing. Supply chains are a much more popular topic. In addition, one might question the degree to which these papers reflect a change in how simulation is used in actual manufacturing applications.

3.4 Manufacturing Research Papers at WinterSim

There are at least two manufacturing industries in which simulation has played a major role—automotive and semiconductor (there are others, of course, but space limitations constrain our discussion). If we search the Winter Simulation Conference proceedings for papers using the terms “automotive or automobile” we find approximately 75 relevant publications, and if we search on “semiconductor” we find 349. A rather informal assessment of these papers reveals:

- “Methodology” papers—either simulation methodology or industry-specific methodologies—constitute one-third of the automotive and 18% of the semiconductor contributions. Very often, these contributions propose some innovation, and use a relatively simple example as the illustration.
- Among the “automotive” papers, flow/material handling-related issues, process-specific analyses, and supply chain oriented contributions are all about equally represented and about 10-15% each of the total

- For “semiconductor” papers, by far the largest fraction—almost one-fourth of the total—address scheduling; quality issues, material handling systems, process tools and production planning all are about equally represented at roughly 10% each of the total.

One would like to think that the “methodology” contributions lead to identifiable changes in both research and practice, but the evidence for that is rather spotty. Material handling is a significant topic for both industries, although the focus is rather different in each. For automotive, the issue is more one of designing to requirements, whereas in semiconductors, there is much more concern with the control of the material handling system to support scheduling. In automotive manufacturing, the details of flow control are not so important. This is perhaps not surprising, given that contemporary automotive assembly plants essentially embed all the flow control decisions into the design of the assembly process. The situation is quite different in the semiconductor industry, where controlling the flow is far and away the most frequently researched issue.

3.5 Impressions

We certainly make no claim to know everything that is in every one of the more than 25,000 journal papers or the nearly 1500 Winter Simulation Conference papers on simulation in manufacturing. But having looked at many of these papers over the past 30 years of teaching and research, there are some defensible observations.

The vast majority of manufacturing simulation papers are very specific, to a particular case study or a particular modeling method or a particular analysis method. While this vast body of archival publication is rich with content, it is fairly difficult to extract from it many general themes, “natural laws,” or engineering principles. As a consequence, perhaps, there are very few textbooks on manufacturing simulation, aside from simulation-tool-specific textbooks which use manufacturing examples to demonstrate tool-specific modeling constructs.

What seems to be missing from the published research, at least as an identifiable theme, is research that builds a theoretical modeling foundation that is specific to manufacturing simulation. Instead, manufacturing is, for the most part, simply a “use case” for demonstrating some particular simulation idea.

4 MANUFACTURING SIMULATION PRACTICE

Here, we present some observations based on our discussions with both researchers and practitioners, and our own experiences as both researchers and advisors to industry.

4.1 Tools of the Trade

The reason discrete event simulation is a valuable tool in practice today is because of the existence of useful software tools for creating simulation models, providing their inputs, executing them, and analyzing their outputs. It must be noted that the users of these tools today owe a great debt of gratitude for their rapid evolution to A. Alan B. Pritsker. He and his many students and collaborators created some of the earliest simulation tools that found widespread use in manufacturing, such as GASP and SLAM. Wilson and Goldsman (2001) give a thorough description of his many contributions to the field.

4.2 Looking Back

Simulation is heavily used in both automotive and semiconductor manufacturing, but the emphasis is rather different in the two. Here we provide a very brief and incomplete assessment of the traditional use of simulation in each.

In designing the automotive factory, the critical metric is the target production rate, which establishes the cycle time for every station in the line. The design problem is to assign every operation to some station, to achieve the desired cycle time while minimizing the investment, and this problem is revisited once a year as the models change. There are not many “routes” through the automotive manufacturing process, thus managing the flow is not a difficult problem, except perhaps around painting.

In designing the semiconductor factory, the key metric is the bottleneck capacity – typically photolithography, because it is the most expensive process. The rest of the factory design is driven by the need to maximize the throughput of the bottleneck process. New products are continuously being introduced and product mix changes constantly, so the fab typically experiences constant changes in the process tools and layout. Because of the re-entrant flow (essentially a sequence of processes is repeated for every “layer” of the device), common process tools and temporary storage of work in process (WIP), there are a very large number of possible routes through the fab. Thus, managing the flow is a fundamental challenge.

In automotive, the focus traditionally has been on design, in making sure that the factory design that is implemented will actually be able to produce automobiles at the desired rate, which is, relatively speaking, fairly constant. In automotive manufacturing, designing to a “steady state” future has been appropriate, because the intended future flows are very predictable. Simulation is critical for making sure that the variability inherent in manufacturing processes is accommodated by the station cycle time. In automotive manufacturing, there has been almost no use of simulation to guide operational manufacturing decisions, although there is growing interest in using simulation to support supply chain decisions. Thus, automotive simulation has depended upon the ability to represent the manufacturing flow processes accurately. The sources of uncertainty have been reasonably well-understood, and thus could be modeled with reasonable fidelity using commercial off-the-shelf (COTS) simulation tools. Thus, in automotive manufacturing, it has been quite feasible to develop reusable libraries of simulation components to represent specific manufacturing processes, and simulation models have not needed to be “persistent”.

The situation in semiconductor manufacturing has been quite different, because the flows are not very predictable. The phenomenon of the “WIP bubble” (Cunningham and Shanthikumar 1996) is well-known, and both factory design and operational strategies to ameliorate WIP bubble effects have been of great interest, due to its disruption to both cycle times and bottleneck utilization. Thus, a great deal of interest has focused on how to manage flow through the factory. In the early years of simulation in semiconductor manufacturing, significant benefits were seen in supporting the designing of automated material handling systems (Pillai 1989). From those successes, the application of simulation to the design of flow control systems, especially scheduling rules, became widely accepted. Today, the leading edge applications use real-time data from the fab to populate a fab simulation in order to develop short-term (4 to 8 hours) strategies for managing both flows and resource assignments. These types of simulations require high-fidelity representations of flow controls, e.g., for batching, queue discipline, WIP storage/retrieval, tool assignment, etc. Contemporary commercial off-the-shelf (COTS) simulation tools do not provide the modeling constructs to support this level of fidelity, so in semiconductor fab simulations, much of the control system modeling is done by extending the COTS tools with custom code. The dependence on simulation as an integral part of the fab planning and control processes requires reliability and models that are continuously updated to reflect resource changes in the fab.

Simulation has become an essential decision support for both automotive and semiconductor manufacturing, but the histories have been somewhat different. In automotive, it simply is not acceptable to design a final assembly plant and then “tweak” it to overcome design flaws. Simulation provides the ability to test design decisions before they are implemented, so making changes is much cheaper. In essence, as assembly plants became more automated – and thus more expensive – there was really no alternative to simulation as cost-avoidance insurance. In semiconductor manufacturing, while simulation is, today, an integral part of planning and control, it did not start out that way. Rather, successes in the early applications of simulation to the design of material handling automation generated sufficient trust among senior managers that simulation was used to evaluate flow control policies. Success there lead to the use of simulation as an integral part of short term planning and control.

In both automotive and semiconductor manufacturing, the enterprise must maintain a staff of simulation experts, whose function is to develop, maintain, modify, and execute the simulation models that are critical to supporting factory design and operations decision making. This is true, as well, for other industries and large firms who routinely use simulation to support decision making.

If we look beyond the large firms with dedicated simulation experts on staff, the role of manufacturing simulation is much less prominent. In fact, a question asked at almost every Winter Simulation Conference is "Why isn't there greater application of simulation in industry?". There are a number of inhibiting issues. First, there are organizational issues. Despite its successes, manufacturing simulation shares the same principle problem as other "math-dependent" abstraction-based analysis approaches. On all organizational levels of the manufacturing company you will find some people who understand these methods and appreciate their value and some people who will be skeptical, either because they have not seen successful applications, or because they have seen unsuccessful ones. This is a fundamental problem which is extremely hard to solve. In an attempt to win over these simulation sceptics, simulation models may become more detailed than is needed. These unneeded details lead to higher modeling cost and to higher data demand, increasing cost even more, and introducing risks associated with modeling errors or insufficiently vetted data.

There are modeling competency issues. To develop a useful model of a moderately complicated manufacturing process requires a considerable level of expertise – considerably more than the typical graduate engineer possesses right out of school. So, significant levels of experience and mentoring are required for a simulation engineer to be considered competent to create a useful model. This level of competence can only be sustained through constant practice. By the same token, the simulation tools may make it easy to construct trivial models, but constructing large complicated models requires deep knowledge of the tool, which also requires constant practice to sustain. One cannot be a part-time manufacturing simulation expert. One concern expressed from both automotive and semiconductor firms is that undergraduate degree programs are no longer turning out young engineers who want to join a simulation team and become a simulation expert. The dominance of "drag and drop" interfaces for simulation modeling tools simultaneously gives the false impression that simulation modeling is "easy" and prevents the development of the modeling and coding skills necessary to develop customized event handlers or control logic.

Another issue is data, whether from a planned or existing system. Even after more than 50 years of manufacturing simulation, almost all simulation projects must deal with inadequate data availability and/or data quality problems. Again, this has obvious reasons which are hard to overcome. First and foremost, high-quality data collection is expensive. A management that is not convinced about the value of simulation will not spend the money to enable the necessary supporting data collection. In addition, there is a principal problem: often the data which has the greatest impact on model result fidelity also has the worst statistical quality because of its small sample sizes. All companies try as much as possible to avoid breakdowns, long repair times, and other events that disrupt flow, i.e., try to make them "rare events". As a consequence, there simply is not much related data to support simulation.

Finally, for the last 50 years simulation experts have not been able to provide reasonable estimates for the return on investment for simulation studies. Even a simulation-sceptical manager would buy a $100K study for an expected return of say $1 million. But such numbers are still not available despite the huge number of completed simulation studies. In other words, when we get beyond those situations where there is no alternative to simulation, and consider situations where simulation "might" be effective, it is very difficult to make a case for the necessary investment.

In summary, the typical roadblocks for the application of simulation for manufacturing systems are similar to what we see for other math-based methods.

4.3 Looking Forward

There is no shortage of evidence indicating that manufacturing is changing rapidly. Practically unlimited bandwidth, cloud computing, big data, visualization, machine learning and artificial intelligence seem to promise a manufacturing future where ubiquitous data is presented through real-time dashboards, and decision makers have access to high-quality, fast, cheap decision support. The Internet of Things, Industry 4.0 and the digital thread hint at factories and supply chains that are tightly integrated and can respond to contingencies in real time. What do all these technological innovations imply for the practice of simulation?

Likewise, if we look at the arc of simulation software development, the emphasis seems likely to be focused on developing ever better visualization, including virtual reality, and ever more elaborate libraries of “drag-n-drop” components. Can these libraries keep pace with the evolution of manufacturing?

Large, tightly integrated manufacturing systems are not going to be easier to model than their less-tightly integrated predecessors, regardless of the breadth of the model component libraries. Thus, the challenge of modeling competency is not diminishing. Can a single modeling expert master all the interacting systems? Or do we need to start preparing for a future where multiple simulation modeling disciplines must collaborate?

The data problems of the future are as likely to be caused by a surfeit of data, as by the lack of data, and the difficulty may well be deciding what to do with so much data, and whether the data really needed is included. This presents challenges both to the research community and to education. Simulations for short term planning and scheduling already represent a non-steady-state analysis, and the situation becomes even more complex if we think about real-time data input to simulations as they are running.

5 CONCLUSIONS

The fundamental problems of fidelity, time and cost remain largely unsolved, some 60 years after the first digital discrete event simulation models. Where there is no alternative to simulation, and the risks of not doing simulation are too great, simulation will remain a viable solution. But as long there are not better solutions to the fidelity, time and cost problem, manufacturing simulation will not achieve its full potential. How might the manufacturing simulation community go about addressing this need?

First of all we should stop thinking or claiming that manufacturing simulation is straightforward and that it is only a matter of better tools to pave the path for non-experts to create high-quality simulation models. We’ve witnessed a continuous evolution in simulation tools, hand-in-hand with better computers and better software engineering approaches. As soon as a new programming paradigm appears, there is a new set of state-of-the-art tools available to the simulation modeler. This will continue with the integration of even larger amounts of online data and even better model animation, e.g., the first tools already offer virtual reality capabilities.

But the fundamental problems remain: Building abstract models will continue to be an expert business, even more when in-depth computer science knowledge is required to integrate the data collection into the modelling process because the future factory information technology (IT) systems will become too complex to be dealt with by IT novices.

The ability to understand complex systems on a rather abstract level will continue to be a requirement for a good modeler, independently from the development of new simulators because there is no computer support available to replace the decision of a human modeler about model boundaries, components and levels of detail.

The same situation can be found for experimentation and result interpretation. Random effects on a large range of time horizons are a fundamental characteristic of manufacturing systems, for instance, stochastic times for processing, transport (seconds or minutes), breakdown (days, weeks or months) or repair (hours or days). As a consequence, effective simulation of large, tightly integrated manufacturing systems will always require expertise in design of experiments and statistics. New supporting software tools will help to tackle an increasing amount of experimentation and resulting data but the setup of the experiments and the interpretation of the results will still need a human expert in the future.

We must face the fact that modeling manufacturing is hard, and more than can be done reliably from an *ad hoc* approach. It is time for the manufacturing community as a whole, not just the manufacturing simulation community, to recognize this fact and begin to develop a higher level, more abstract language for thinking about and describing the manufacturing systems for which we need analysis models. The manufacturing simulation community should be in a position to lead this effort, since we already work routinely with abstract (simulation) models. Today the designers of integrated circuits use a common set of abstractions to describe their devices, and automatically generate the analysis of those devices, including simulations. What if we took as a future vision that we should be using a common set of abstractions to describe the integrated circuit factory, and from that description, we should be automating the generation of simulation models? The pursuit of that vision would have profound implications for the problems of fidelity, time and cost.

Industry is worried about the simulation “labor force”, i.e., the technical talent needed to develop, maintain, execute and interpret large-scale complex simulation models. To address this need, we will have to invest in developing an attractive simulation curriculum to attract more young people to a career as an expert in simulation. Yes, it will contain a lot of math and abstract thinking but this is the only choice to tackle the problems of our increasingly complex world.

Finally, we must find a way to present a more compelling “value proposition” for simulation in those situations where it is not the only alternative. We might begin by being clear about how simulation supports decision makers, and what the alternatives are to “smarter” decisions. A common experience is the decision maker who would prefer to invest an additional $250K in machinery rather than to trust “smarter scheduling” that is “proven” using a $50K simulation. To be more convincing to the potential in-house customers and stakeholders of simulation we will have to be more precise about the cost and potential benefits of a simulation study.

Manufacturing simulation has come a long way since Jackson’s first studies, and for many companies has a fundamental role in decision making. But manufacturing simulation is far from ubiquitous, so there is tremendous room for growth. That growth will likely not come from pursuing the research and development business as usual, but from learning to think about manufacturing more abstractly, and developing a new generation of modeling tools.

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