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Review

Simulation for manufacturing system design and operation: Literature review and analysis

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ABSTRACT

This paper provides a comprehensive review of discrete event simulation publications published between 2002 and 2013 with a particular focus on applications in manufacturing. The literature is classified into three general classes of manufacturing system design, manufacturing system operation, and simulation language/package development. The paper further categorizes the literature into 11 subclasses based on the application area. The current review contributes to the literature in three significant ways: (1) it provides a wide coverage by reviewing 290 papers; (2) it provides a detailed analysis of different aspects of the literature to identify research trends through innovative data mining approaches as well as insights derived from the review process; and (3) it updates and extends the existing classification schemes through identification and inclusion of recently emerged application areas and exclusion of obsolete categories. The results of the literature analysis are then used to make suggestions for future research.

Contents

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1. Introduction

As a powerful tool for analyzing complex stochastic systems, computer simulation has been commonly used in a wide spectrum of fields including but not limited to healthcare [1], marketing [2], supply chain [3], and military [4]. In particular, simulation has played a significant role in evaluating the design and operational performance of manufacturing systems. Successful applications of simulation in many practical real-world problems have proved its effectiveness in approaching various problems in the manufacturing sector.

The general topic of simulation and the use of different simulation software have been addressed in several books (see, Kelton et al. [5,6], Law [7], Banks et al. [8], Ross [9]). Several publications have also discussed different aspects of simulation modeling including verification and validation of models, and conducting and analyzing simulation experiments (for example, Law [10,11], Robinson [12], Fischbein and Yellig [13], Baines et al. [14]).

Discrete event simulation (DES) is one of the most commonly used techniques for analyzing and understanding the dynamics of manufacturing systems. It is a highly flexible tool which enables us to evaluate different alternatives of system configurations and operating strategies to support decision making in the manufacturing context. As a computationally expensive tool, the increase in computer power and memory has further increased the use of discrete event simulation in recent years.

Simulation has been successfully adopted in numerous studies related to manufacturing system design and operation which has led to an increased interest in this research topic. Recently, there have been several survey articles in the literature on the application of simulation to manufacturing systems. Table 1 provides a list of these review papers published since 2002. However, these review papers are either too broad to specifically discuss discrete event simulation and its applications to manufacturing systems or too limited on the use of simulation in a specific and relatively narrow area within the manufacturing context. In addition to the simulation surveys discussed above, there have been several manufacturing related survey papers that do not exclusively discuss simulation applications yet cover a number of related simulation studies. Table 2 presents a list of these review papers. Although some of these papers classify and discuss studies involving simulation as a separate category/sub-category in their respective classification schemes, there is still the need for a comprehensive literature review focusing on discrete event simulation and its contributions to the general topic of manufacturing.

The current paper focuses on the application of discrete event simulation to a broad and extensive range of manufacturing system design and operation problems. We will also discuss the development of simulation frameworks, software tools, metamodeling, and optimization methods with specific application to manufacturing systems. This survey is a follow-up to an earlier survey paper by Smith [33]. This paper updates and extends the classification developed in the earlier paper and covers 290 papers published from 2002 to 2013. The literature search was conducted using different keywords and combinations thereof. As an example, a keyword combination (simulation and manufacturing) searched in the title/abstract/keywords generated approximately 3000 papers published since 2002. The entire search process generated approximately 12,000 papers, which were then narrowed down to 2200 papers mainly by abstract reviewing. Further filtering was then done by full-text reading. The reference chasing method was then used to add more papers to the list. The findings from the review process together with our trend analysis through text mining indicate a general shift in the application of discrete event simulation from the design to operational aspects of manufacturing systems.

The remainder of the paper is organized as follows: Section 2 describes the classification scheme for the application of discrete event simulation in manufacturing systems. Sections 3–5 review the literature in each class and subclass. In Section 6, interesting observations from the literature review are discussed and innovative data mining approaches are employed to extract trends to shed more light on the current state of the literature. Finally, conclusions and considerations for future research are provided in Section 7.

2. Classification

In this survey, we follow and extend the classification developed by Smith [33]. The three general classes are manufacturing system design, manufacturing system operation, and simulation language/package development. The papers in the literature are also classified into 11 subclasses based on the application area, as shown in Table 3. The table also compares the current paper and the earlier survey in terms of the number of references in each category.

In this paper, several changes have been made to the initial classification scheme based on our recent findings. The categories "maintenance operations planning and scheduling" and "simulation metamodeling and optimization methods" have been added to the classification. Moreover, the general class of "simulation language/package development" has been further divided into three subclasses, as shown in Table 3. A final change in the classification is the elimination of the "Performance Analysis" subclass due to its overlap with other categories. However, the removal of this category should not be interpreted as necessarily indicating that simulation is not used for performance analysis anymore. In fact, due to the descriptive nature of simulation, most of the simulation studies could be classified under this general topic.

In the current paper, we have listed the papers in the most applicable category since some papers might not fall exactly into one class. For further descriptions of this classification scheme and discussions about the subclasses, see Smith [33]. Finally, in order facilitate reading, some of the sections are further grouped into subsections. These subsections are not part of the proposed classification scheme and thus are not included in Table 3.

3. Manufacturing system design

The manufacturing system design class has been subdivided into the general system design and facility layout, material handling system (MHS) design, cellular manufacturing system (CMS) design, and flexible manufacturing system (FMS) design. The following sections describe each of these subclasses in more detail.

Table 1
Review papers on simulation applications in manufacturing systems.

Reference	Application	Objective (comments)
Jahangirian et al. [15]	Manufacturing and business	Role of simulation techniques including DES and system dynamics
Ingemansson et al. [16]	Manufacturing industry	Use of DES in manufacturing and energy sectors in Sweden
Chan et al. [17]	Flexible manufacturing systems (FMS)	Simulation for FMS scheduling
Chan and Chan [18]	FMS	Simulation as analyzing tool for FMS scheduling
Mahdavi and Shirazi [19]	FMS	Simulation-based intelligent decision support systems for real-time control of FMS
Chtourou et al. [20]	Cellular manufacturing systems	Use of simulation for comparing cellular and functional layouts

Table 2
Related survey articles used in this paper.

Reference	Application	Objective (comments)
Vis [21]	Automated guided vehicles (AGV)	Design and control of AGV systems in different sectors including manufacturing
Agrawal and Heragu [22]	Automated material handling (AMH)	AMH approaches in semiconductor industries
Montoya-Torres [23]	Automated wafer-transport systems	Facility layout and AMH systems design
Jimenez et al. [24]	Semiconductor manufacturing systems	Classify literature by the level of capacity/AMHS details in the model
Jerbi et al. [25]	Functional and cellular layouts	Comparison of functional and cellular layouts
Ruiz and Vázquez-Rodríguez [26]	Hybrid flow shop scheduling	Exact heuristic and metaheuristic methods
Allahverdi et al. [27]	Scheduling	Scheduling problems with setup times or costs
Ernst et al. [28]	Staff scheduling and rostering	Staff scheduling problems, models, and solution algorithms
Gordon et al. [29]	Common due date assignment	Deterministic models involving single and parallel machines
Gupta and Sivakumar [30]	Job shop scheduling	Job shop scheduling methods in semiconductor manufacturing
Brennan [31]	Real-time control	Real-time distributed intelligent control systems for industrial applications
Castillo and Smith [32]	Manufacturing cell control	Comparison of formal modeling methodologies

3.1. General system design and facility design/layout

Facilities design is an important factor impacting the general performance of manufacturing systems. Facility layout design deals with the allocation of machines/departments in a facility and can have a large impact on the effectiveness and efficiency of manufacturing operations. An effective layout can reduce manufacturing costs and improve the system's performance. Discrete event simulation is an appropriate tool to evaluate the current layout, show potential areas for improvement by evaluating different layout alternatives. Therefore, several researchers have applied simulation in different facility layout problems.

Jagstam and Klingstam [34] use discrete event simulation as an aid for conceptual design and pre-study of manufacturing systems through developing a virtual factory. They propose a simulation handbook to fully integrate simulation as a tool in engineering processes. They also identify the problems associated with the integration of discrete event simulation into the design of manufacturing systems. Greasley [35] develops a simulation model to estimate the storage area required for a textile manufacturing facility. Wang et al. [36] propose a simulation optimization approach based on genetic algorithm (GA) and simulation to resolve the facility layout problem. The application of the proposed approach is illustrated through a case study. Using computer simulation, Altuntas and Selim [37] evaluate and compare several new weighted association rule-based data mining approaches for facility layout problem. Vasudevan et al. [38] describe the application of simulation along with bottleneck analysis, work measurement, floor space requirements and facility layout analysis to increase reliability and profitability of steel-mill manufacturing. In [39], an intelligent search algorithm for deriving assembly line design alternatives is proposed and embedded in a software capable of automatically generating discrete event simulation models for performance analysis. Chan and Chan [40] present a case study in which they use simulation and expert systems to evaluate different design alternatives for a new Printed Circuit Board (PCB) manufacturing system. They predict the feasibility of each design by evaluating machine utilization, waiting time, and throughput obtained from the

Table 3
Areas of simulation application in manufacturing.

Class (section no.)	Current paper		2002 survey	
	Number	%	Number	%
Manufacturing system design				
General system design and facility design/layout (3.1)	18	6	16	8.5
Material handling system design (3.2)	18	6	25	13
Cellular manufacturing system design (3.3)	14	5	22	12
Flexible manufacturing system design (3.4)	8	3	29	15.5
Manufacturing system operation				
Manufacturing operations planning and scheduling (4.1)	87	30	26	14
Maintenance operations planning and scheduling (4.2)	20	7	–	–
Real-time control (4.3)	48	16	29	15.5
Operating policies (4.4)	8	3	4	2
Performance analysis	–	–	18	9.5
Simulation language/package development				
Generic simulation models (5.1)	10	3.5	19[a]	10
Simulation/modeling methods, frameworks, software tools (5.2)	26	9		
Simulation metamodeling and optimization methods (5.3)	33	11.5	–	–
Total papers	290		188	

[a] The "Generic simulation models" and "Simulation/Modeling Methods, Frameworks, Software Tools" subclasses were classified under the same category in Smith [33].

simulation experiments. Owens and Levary [41] develop several designs of a food production line and use simulation to compare the proposed designs with the current line design. Through simulation and industrial applications, Azzi et al. [42] compare the classical approach to configure mixed assembly systems with an innovative proposed approach that aims to minimize both idle and overload times and reduce required buffer capacity.

Uncertainty within the manufacturing systems can significantly affect the efficiency of a facility layout. For instance, an error in the assessment of the product demand may result in an inefficient layout. However, traditional facility layout methods, including most analytical models, cannot be easily used to capture this uncertainty. Azadeh et al. [43] propose an innovative integrated algorithm based on simulation and data envelopment analysis (DEA) for job-shop layout optimization. Their proposed algorithm is capable of modeling and optimizing stochastic and non-linear single-row facility layout problems with ambiguous data. They also apply their method to an injection molding process in a refrigerator manufacturing company. Jithavech and Krishnan [44] present a simulation-based method to develop an efficient facility layout design under uncertainty in the product demand. They quantify the impact of stochastic demand in terms of risk and show that their method can significantly reduce the risk associated with the layout. Mendes et al. [45] use simulation models to derive different performance measures of a mixed-model PC camera assembly line in order to help tune the line configuration for varying levels of demand. Amiri and Mohtashami [46] relax the typical restriction of having deterministic or exponentially distributed processing times, time between failures, and repair times and propose a simulation-based methodology for buffer allocation in production lines. In another study, Staley and Kim [47] present the results of simulation experiments on buffer allocation in closed serial production lines consisting of reliable and unreliable workstations and show that optimal buffer allocation in these systems are less sensitive to bottleneck severity than in open production lines.

Additional applications of simulation in facility design/layout are presented in Moon et al. [48], Yang et al. [49], Wirabhuana and Yogyakarta [50], and Lejtman et al. [51].

3.2. Material handling system design

3.2.1. General MHS design

Material handling system (MHS) has a great impact on the performance of manufacturing systems. The design of the material handing system has been the focus of many studies since a significant part of the total production cost is related to material handling. Due to the increased complexity of these systems, which makes analytical models less efficient, discrete event simulation has been found as an effective tool to solve MHS design problems. Hao and Shen [52] propose a hybrid simulation approach to model complex material handling processes in an assembly line. Their approach consists of discrete event and agent-based technologies which facilitates the implementation of an adaptive environment to simulate different configurations and real-time situations. Durieux and Pierreval [53] study an automated manufacturing system design composed of parallel machines sharing a material handling resource. Through regression metamodeling of a stochastic simulation model, they identify the important factors to improve system performance.

In order to increase productivity, product quality, and system flexibility, automated guided vehicle (AGV) systems have been frequently used in manufacturing environments, especially in flexible manufacturing systems and semiconductor fabrication facilities. The design and operation of AGV systems are highly complex due to high levels of randomness and large number of variables involved. This complexity makes simulation an extremely useful technique in modeling these systems. Vis [21] presents a survey of work involving design and control issues of AGV systems in manufacturing, distribution, transshipment and transportation systems. Several simulation-based models are discussed and it is concluded that most of these models can be applied in manufacturing settings. It is suggested that new analytical and simulation models are needed to be developed for large AGV systems in order to deal with large computation times, NP completeness, congestion, deadlocks, and finite planning horizons. Hsueh [54] proposes a load exchangeable AGV system design in which two AGVs can exchange their loads and their scheduled tasks. Simulation experiments are carried out to show the efficiency of the new system design with regard to different performance measures. Lim et al. [55] propose a construction algorithm to design guide path networks for automated guided vehicle systems and evaluate the performance of the proposed algorithm through a simulation study.

3.2.2. MHS design for flexible manufacturing systems

AGV systems play an important role in flexible manufacturing systems since they can be easily modified to respond to different changes in the system including changes in the demand, product mix, and job priorities. Koo and Jang [56] present stochastic models for AGV-based material handling systems. In their study, they focus on vehicle travel time as a fundamental parameter in solving various flexible manufacturing system design problems. Um et al. [57] present a hybrid method that combines simulation-based analytical and optimization techniques for an FMS with AGV systems to satisfy three objectives of minimizing congestion, maximizing vehicle utilization, and maximizing the throughput. Lee and Srisawat [58] investigate the interaction between operation strategies and manufacturing system constructs in a multiple-load AGV system. They propose several heuristic rules for load selection and use simulation to evaluate the performance measures under two manufacturing system designs, i.e. job-shop and FMS.

3.2.3. MHS design for semiconductor manufacturing

Semiconductor manufacturing systems are highly sophisticated environments due to the very large number of processing steps and re-entrant flows which create a large amount of material flow between bays. Varying product mixes and sequence-dependent setups make these systems even more complicated. Furthermore, the equipment performing different operations on wafers are very expensive – constituting about 80% of the capital cost of the fab. Therefore, MHS design and production planning and scheduling are critical to these systems. Discrete event simulation is one of the best candidate tools for studying such dynamic and complex systems. As a result, semiconductor manufacturing has received a significant amount of attention in the simulation literature. In this section, we present research publications describing the use of simulation for MHS design in semiconductor manufacturing. However, simulation has also been widely applied to other operational areas within these systems. Section 4.1 provides a large number of articles describing the application of simulation to solve scheduling problems in semiconductor manufacturing systems, and Section 4.2 presents some work on scheduling of preventive maintenance operations in semiconductor fabrication facilities.

Optimized design of automated material handling system results in increased yield and reduced cycle times in the semiconductor manufacturing industry where material must be transported not only within a bay (intra-bay) but also from one bay to another (inter-bay). A 300-mm wafer visits hundreds of process tools to undergo many processing steps. Therefore, automated material handling systems (AMHS) are key aspects in 300-mm wafer fabs and simulation is a widely used tool to analyze and optimize AMHS design in order to reduce transportation time and cost. Jimenez et al. [24] identify a method to classify a fab model by the level of capacity and AMHS details. The classification method can serve as the basis of a framework to select the system components to be modeled within a desired level of detail for accurately planning the capacity of these facilities. Their classification framework can be applied in manufacturing settings that use any sort of AMHS. The paper then reviews and classifies simulation studies by level of capacity/AMHS detail. Nazzal and Bodner [59] describe a two-level framework for designing AMHS for 300 mm wafer fabs. They make use of a simulation model which incorporates the AMHS to make and analyze design decisions. To solve the AMHS allocation to interbay and intrabay systems in 300 mm wafer fabrication facilities, Huang et al. [60] develop a simulation model of a real world fab and use a simulation optimization technique to obtain the optimal vehicle allocation. Pillai et al. [61] present results of the implementation of 300-mm full-factory simulation tools supporting Intel's factories. The presented tools integrate AMHS behaviors and model dynamic interactions among production tools, manufacturing technicians, and automation systems.

Kong [62] introduces an additional production simulation step to apply the production logic to the AMHS simulation model. The AMHS simulation step follows the production simulation step in order to predict the throughput of the semiconductor line and estimate the scope of investment in AMHS. Kondo [63] describes a new simulation framework to estimate the productivity of a semiconductor fab prior to installation of an AMHS. Kiba et al. [64] present a detailed simulation model of the production system and AMHS for a 300 mm semiconductor plant and claim that the proposed full-scaled simulation model gives precise results and understanding of the detailed behavior of local or global parts of the fab. Montoya-Torres [23] provides a review of several articles concerning the use of simulation for facility layout and MHS design for integrated circuit semiconductor manufacturing industry. Agrawal and Heragu [22] give a review of various approaches for automated material handling in semiconductor manufacturing industries. Some of the reviewed papers involve the use of simulation for analyzing equipment utilization and facility layout. Sturm et al. [65] outline the planning approach for two typical AMHS designs used for interbay transportation in 200 mm wafer fabs. The models they use are generic and can be applied to different AMHS problems.

While a few studies address the general topic of MHS design, the majority of the papers study simulation applications in AMHS design for semiconductor manufacturing systems and AGV system design. According to Smith [33], the general topic of MHS design was a very popular area for the application of simulation; however, there has been a noticeable decrease in the number of these publications over the past few years. This trend suggests that as the design of material handling systems has become more mature, the attention has shifted to other operational aspects of these systems (see Section 4).

3.3. Cellular manufacturing system design

Cellular manufacturing is the implementation of group technology in manufacturing systems in which families of parts requiring similar manufacturing processes are grouped together and processed in a manufacturing cell designed to manufacture the corresponding product family. The cellular manufacturing system (CMS) results in a series of enhancements in manufacturing operations by reducing setup and lead times, work in process (WIP), material handling and production planning and control costs. The main issues in cellular manufacturing system design are formation of cells and generation of part/product families.

Neto and Filho [66] propose a multi-objective optimization approach to solve the manufacturing cell formation problem. Their approach is capable of generating a set of alternative manufacturing cell configurations while optimizing multiple performance measures. Reeb et al. [67] use discrete event simulation to develop and select part families for cell manufacturing of a wood products company. Durmusoglu and Satoglu [68] propose a design methodology based on axiomatic design principles for cellular manufacturing systems. In the proposed approach, simulation is used to identify and eliminate bottlenecks.

Siemiatkowski and Przybylski [69] highlight the issues of multistage process planning within cellular flexible manufacturing systems under the consideration of multiple choices of process routings. In their proposed framework, they investigate alternative process flows via simulation. Azadeh et al. [70] present an integrated methodology for optimization of operator allocation in CMS. They develop a simulation model to evaluate various layouts and use fuzzy data envelopment analysis to assess the simulation results. They apply the proposed methodology to a real case study. In a similar study, Azadeh et al. [71] use computer simulation and genetic algorithms to find optimum operator assignment with respect to cellular condition in a CMS. In another study, Ertay and Ruan [72] present an approach based on DEA to determine the most efficient labor assignment in CMS. They use simulation experiments to compare the efficiency of different alternative labor assignment scenarios. For a similar study see Azadeh and Anvari [73]. Egilmez et al. [74] propose a non-linear mathematical model to solve the cellular manufacturing system design problem under stochasticity and use simulation to both validate the compare the proposed model with its deterministic version. Ranaiefar et al. [75] study material flow in a CMS and use simulation to determine the proper flow of material with the objective of achieving company's development plan as well as increasing the production capacity. Savory and Williams [76] describe a discrete-event simulation model of a U-shaped manufacturing cell and the integration of it with activity-based costing (ABC) concepts cost estimation and analysis of the manufacturing cell design.

A number of simulation studies have been devoted to compare the cellular layout (CL) with the functional layout (FL). Jerbi et al. [25] categorize these studies as simulation based investigations, analytical models, and empirical surveys. They present a taxonomy of the key factors used in the FL-CL comparison simulation studies and claim that simulation studies represent the mainstream of the work in this domain. They also developed simulation models for both layouts with the intention to be the key instruments in establishing an objective simulation-based FL-CL comparison methodology. Pitchuka et al. [77] investigate the transition from a functional system to a cellular system by obtaining queue times for both systems through queueing theory, for single-stage, and simulation, for multistage production under identical settings of process time, setup time, batch size and part arrival. They also identify the situations where a cellular system outperforms a functional system. Chtourou et al. [20] give a taxonomy of the main experimental factors and performance measures used in the main simulation studies comparing the CL and FL system layouts with a focus on the objectivity of the layout comparison methodologies. They further use simulation to illustrate some of the shortcomings of these methodologies.

3.4. Flexible manufacturing system design

Flexibility equips manufacturing systems with the ability to efficiently respond to fluctuations in demand levels for the products being produced as well as other uncertainties such as machine failures and stochastic processing times. Reduced labor requirements, improved machine utilization, enhanced operational control, and reduced WIP are among the other advantages that flexibility offers to manufacturing facilities. An FMS is an integrated production system consisting of multi-functional numerically controlled (NC) machines, an automated material handling system, and a computer control system for integrating the NC machine and the AMHS. FMS problems can be classified as design, planning, scheduling, and control problems. Although the main body of the recent works on FMS has been on the operational aspects of these systems, several researchers have used simulation to address issues concerning the design of flexible manufacturing systems. The multi-dimensionality of FMS design adds a level of complexity to these problems which makes them beyond the reach of many analytical models and provides a suitable environment for the application of computer simulation.

By providing a discussion on interesting results of several simulation studies on flexible manufacturing systems, Wadhwa et al. [78] conduct a conceptual study and simulation experimentation to understand the exact mechanism that enables flexibility to reduce lead time. Chan et al. [79] focus on the physical and operating characteristics of alternative machines to investigate the effect of these characteristics on the level of flexibility in an FMS. They propose an approach to identify productive and counterproductive performance zones of an FMS and use a simulation model of a hypothetical manufacturing system to answer the question of whether an increase in flexibility will have the expected benefits and up to what level of flexibility we can expect improvements. In a similar study, Chan [80] investigates the effects of different levels of operation flexibility on the performance of a flexible manufacturing system. Simulation results show that increased operation flexibility does not necessarily yield better performance. Suresh Kumar and Sridharan [81] study a typical FMS design with a tool-sharing environment. They develop a discrete event simulation model for the purpose of experimenting different scenarios. They use simulation results to develop regression-based metamodels to predict the performance of the FMS.

A number of simulation studies have been conducted to deal with routing flexibility, as it is a major contributor to the flexibility of an FMS. Joseph and Sridharan [82] focus on the evaluation of the routing flexibility of an FMS with dynamic part arrivals. A discrete-event simulation model is used to evaluate the routing flexibility of a typical FMS configuration. Bilge et al. [83] describe full routing flexibility which includes alternative machines for operations as well as alternative sequences of operations for producing the same part. They introduce three new approaches for dynamic part routing and test the proposed approaches under variable system configurations through simulation experiments. Chan [84] use simulation to analyze different routing policies and the effect of changing part mix ratios under both infinite and finite buffer capacity in an FMS. Ozmutlu and Harmonosky [85] develop a rerouting strategy to minimize mean flowtime of parts in an FMS considering machine failures. The performance of the proposed rerouting heuristic in minimizing mean flowtime is tested via simulation.

4. Manufacturing system operation

The general class of manufacturing system operation has been further subdivided into manufacturing operations planning and scheduling, maintenance operations planning and scheduling, real-time control, and operating policies. The two changes to this general category from the earlier survey [33] are the addition of the new subclass of maintenance operations and the removal of performance analysis as a subcategory.

4.1. Manufacturing operations planning and scheduling

Operations planning and scheduling has received a tremendous amount of attention in the literature in recent years. For a list of review papers on operation planning and scheduling problems, see Ruiz and Vázquez-Rodríguez [26], Allahverdi et al. [27], Ernst et al. [28], and Gordon et al. [29]. A large number of these publications employ discrete event simulation to address different operations planning and scheduling problems.

4.1.1. Long- and short-term production planning

Several studies illustrate the capability of simulation not only for production planning but in providing manufacturing decision makers with a tool to simultaneously account for long term production planning and short term scheduling. Koh and Saad [86] develop a simulation model of an MRP-controlled batch manufacturing system to study production planning and scheduling and to evaluate the delivery performance of the system when disturbed by various stochastic events. Ruiz et al. [87] present an agent-supported simulation tool for decision making in an intelligent manufacturing environment and illustrate its application in a case study of a metal-mechanic manufacturer. In order to manage production level during the diffusion of new products, Negahban et al. [88] present an agent-based simulation model where the manufacturing agent is capable of forecasting the future demand and adjusting its production level. They evaluate the performance of alternative production level management approaches under different levels of production volume flexibility and market dynamics.

By considering robustness, fill rate, and inventory level as three performance measures, Sun et al. [89] use multiple simulation models to compare the performance of dynamic risk-based scheduling (DRS) and MRP tools in single and multi-machine manufacturing systems under demand uncertainty. A hybrid discrete event simulation and system dynamics (SD) is proposed by Jamalnia and Feili [90] to model and simulate the aggregate production planning problem (APP) where the DES module is used to simulate the shop-floor activities at the operational-level while the SD module is used to evaluate a collection of aggregate-level strategic decisions. Musselman et al. [91] describe the integration of a simulation-based scheduling function and Enterprise Resource Planning (ERP) system for producing a feasible schedule. Baykasoglu and Gocken [92] develop simulation models to study simultaneous consideration of job entry, job release, priority dispatching, and shop flexibility as four major decision levels in production planning and control.

A hierarchical production planning and control frame work for FMS is proposed by Albey and Bilge [93] where simulation is used as a capacity anticipation mechanism. Through experimental comparisons using simulation, Kacar et al. [94] compare the performance of three methods for for production planning under workload-dependent lead times, namely a clearing function model and two methods based on iterative linear programing and simulation. Selçuk et al. [95] develop a simulation model to illustrate the effect of updating lead times on the performance of a two-level hierarchical planning system in a stochastic setting. Nandagawe and Sarmah [96] use a simulation model to identify bottlenecks of a steel melting plant in order to find the optimum casting plan horizon. Maas and Standridge [97] develop a generic simulation model to conduct capacity analysis, schedule planning, and target inventory setting software to support operation of cells in the plastic manufacturing industry. Ebadian et al. [98] conduct simulation experiments to validate the performance of a hierarchical production planning structure for make-to-order companies.

4.1.2. General MHS operations

Operation of automated material handling systems and automated guided vehicle systems have also shown to be a fertile area for simulation application. Liang and Wang [99] propose an analytic methodology combining simulation and statistical techniques to develop a modularized simulation method for AMHS delivery time forecast of priority lots. Babiceanu and Chen [100] propose an agent-based material handling system and compared the allocation of material handling operations under the centralized and decentralized scheduling approaches. A simulation study is carried out to assess the performance of the decentralized agent-based approach. In a similar study, Babiceanu and Chen [101] propose a holonic-based material handling system and conduct a series of simulation studies to justify the use of the decentralized holonic approach and assess its performance.

Efficient use of AGVs requires efficient dispatching and load selection procedures to reduce empty and partially loaded vehicles. Several researchers have studied the use of simulation for scheduling and dispatching AGVs in manufacturing systems. Kesen and Baykoc [102] develop a simulation model of a job shop environment involving AGVs based on the just-in-time philosophy and explain how to conduct simulation output analysis and conduct experimental designs in order to examine the effect of different factors on the performance of the system. Roser et al. [103] propose a method to predict the primary and secondary bottlenecks for both steady-state and variable manufacturing systems involving AGVs, computer networks, and supply and demand logistics. The proposed method is also easy to implement in any simulation software. Lacomme et al. [104] propose a method combining branch-and-bound and discrete event simulation to solve the job-input sequencing and vehicle-dispatching problems in a manufacturing environment with a single-vehicle automated guided vehicle system. For a similar study, see Caumond et al. [105].

Singh et al. [106] study the scheduling of AGVs for efficient and uniform material distribution in an automotive manufacturing plant. They propose innovative dispatching rules and use discrete event simulation to evaluate their performance and effect of variation in different design parameters for both single AGV and multiple AGV case. Ho and Liu [107] study the pickup-dispatching problem of multiple-load AGVs. Computer simulations are used to understand the performance of the proposed rules with regard to different performance measures. In their simulation models the vehicles are the bottlenecks causing the performance to be solely dependent on their performance. Different delivery-dispatching, pickup-dispatching and load-selection rules are also evaluated using simulation [108–113].

4.1.3. General manufacturing system scheduling

Simulation has been applied to a variety of short term decision making problems in manufacturing. Thomas and Charpentier [114] show the advantage of developing a reduced model with fewer elements, connections or calculations for scheduling of a manufacturing system. Lejmi and Sabuncuoglu [115] use simulation and statistical analysis to analyze the impact of load, processing time, and due date variation on the performance of the scheduling system in manufacturing environments. Through a simplified simulation model of a pipe manufacturing capacity, Dong and Medeiros [116], aim to minimize cost of batch schedules considering material holding cost, late delivery cost, and changeovers. Ahmadizar et al. [117] study a stochastic group shop scheduling problem. They propose a hybrid algorithm based on ant colony optimization and a heuristic algorithm to generate solutions. A discrete event simulation model is used to evaluate the expected makespan. Chong et al. [118] present a simulation-based real-time scheduling mechanism for dynamic discrete manufacturing. In the proposed approach, discrete-event simulation is used both off-line and on-line. Reference indices based on the performance of different scheduling approaches are built under varying shop floor conditions. Simulation is then used on-line to evaluate different scheduling approaches and the corresponding schedules to determine the best solution. Ehrenberg and Zimmermann [119] present a simulation-based scheduling approach for make-to-order production systems and evaluate its applicability in a real-world case study of a special-purpose glass manufacturer. In their approach, mixed-integer programming is used to generate schedules while its input parameters and constraints are iteratively updated by a simulation model. Simulation has also been used to investigate order release strategies in make-to-order environments [120,121]. Evaluation of due date assignment rules and flow time estimation methods are among other problems that have been tackled by simulation researchers [122–125].

4.1.4. Flow shop scheduling

The literature on flow shop scheduling has also benefited from the contributions of computer simulation. Kuo et al. [126] utilize a simulation model of a flow shop with multiple processors in conjunction with an analytic hierarchy process and Taguchi orthogonal array to analyze the performance of several dispatching rules and find the most suitable rule for every workstation. Azadeh et al. [127] propose a flexible artificial neural network-fuzzy simulation algorithm for solving scheduling problems in flow shops with multiple processors. In a similar study, Yang et al. [128] describe a genetic algorithm for solving a multi-attribute combinatorial dispatching problem where discrete-event simulation is used to evaluate the fitness (objective value) of each chromosome. The quality of the solution obtained from the approach is illustrated by a case study conducted in a multi-layer ceramic capacitor manufacturing plant. Alfieri [129] studies a multiple objective flow shop scheduling problem in a cardboard company with multi-machine stations and sequence-dependent setup times. They present a simulation-based environment in which the production sequence is interactively chosen by a tabu search based heuristic algorithm while a discrete-event simulation deals with the timing aspect. Through a case study of TFT-LCD manufacturing system, Huang et al. [130] develop a simulation model to solve the re-scheduling problems in flow shop mixed-lines. To address the block assembly scheduling in shipyard production and by considering spatial optimization, Zhuo et al. [131] employ discrete event simulation to evaluate and improve system performance. The use of simulation for evaluating the performance of scheduling methods and dispatching rules in flow shops have also been addressed in [132–136].

4.1.5. Job shop scheduling

For scheduling in job shop manufacturing context, Drieel and Mnch [137] conduct simulation experiments to assess the performance of a shifting bottleneck heuristic which integrates AMHS and scheduling operations in dynamic job shops. Using a relatively new simulation package called Simio™ [138], Chongwatpol and Sharda [139] develop simulation models to examine the benefits of an information visibility-based scheduling rule for job shop manufacturing systems that is based on RFID traceability. By integrating three fundamental enterprise systems namely order processing, production scheduling, and activity control, Pereira and Santoro [140] describe a new heuristic method for operations scheduling in assembly job shop systems. The method implements a backward and a forward approach to satisfy due dates and capacity restrictions. The two approaches work iteratively within deterministic and stochastic simulation models of the system. Gupta and Sivakumar [141] present the applications of the Conjunctive Simulated Scheduling (CSS) approach in scheduling job-shop problems. They also discuss the differences between CSS and typical simulation studies. Omkumar et al. [142] study the scheduling of multi-level jobs in static assembly job shops and propose a new heuristic by integrating simulation with genetic algorithms. Simulation for evaluating different due date assignment and dispatching rules in job shops have been studied in [143–147]. For other simulation studies related to job shop systems, see [148,149].

4.1.6. FMS scheduling

Simulation is probably one of the most widely used tools for FMS scheduling. Chan et al. [17] review researches that employ simulation techniques as the analyzing tool for scheduling flexible manufacturing systems. They further classify scheduling methodologies as simulation of general scheduling studies, multi-criteria scheduling approaches, and artificial intelligence approaches. In another survey, Chan and Chan [18] provides a review of scheduling study and future trend of simulation on FMS scheduling. They suggest that simulation combined with artificial intelligence techniques would result in very powerful tools capable of handling a larger variety of FMS scheduling problems. Priore et al. [150] compare machine-learning algorithms for dynamic scheduling of FMS. Simulation results are discussed to show the improvements made by the proposed approach. Cheng and Chan [151] develop a simulation model of a flexible manufacturing system where production and demand data are input from an Excel spreadsheet. The model optimizes part input sequence by evaluating different scenarios of input sequences with the objective of maximizing the total slack time. As an evaluation tool, Siwamogsatham and Saygin [152] use simulation to illustrate the effectiveness of an auction-based algorithm for real-time scheduling of FMS. Domingos and Politano [153] propose an on-line scheduling procedure based on fuzzy logic for shop floor task scheduling. They conduct a simulation study to verify the applicability of the proposed approach. For list of other studies that use simulation to evaluate the performance of different scheduling rules, see [154–159].

4.1.7. Semiconductor manufacturing scheduling

Efficient scheduling is crucial in semiconductor manufacturing in order to meet various objectives regarding cycle time, machine utilization, and due date accuracy. Gupta and Sivakumar [30] present a review on job shop scheduling techniques in semiconductor manufacturing. A number of the reviewed papers involve the application of simulation techniques. Arisha and Young [160] propose a scheduling methodology that integrates two common approaches, simulation and artificial intelligence. They develop a scheduler integrated with a comprehensive simulation model with the objective of reducing WIP, setup time, and throughput time. Lee et al. [161] propose an approach based on timed extended object-oriented Petri nets for multiple-objective scheduling and real-time dispatching for semiconductor manufacturing. Simulation experiments are conducted to validate the proposed approach. Barua et al. [162] propose a heuristic procedure combining the global factory schedule and dispatching rules and use simulation to evaluate the performance of the application of proposed method. Focusing on the wafer test operations, Chen et al. [163] propose a dynamic dispatching approach consisting of a discrete event simulation and lot ranking and lot assignment algorithms to prioritize work in process. Chen [164] proposes two intelligent scheduling rules for a wafer fabrication factory and employs simulation to evaluate their performance. Gupta and Sivakumar [165] propose an approach combining analytical methods and discrete event simulation to generate a near optimal solution for the multi-objective scheduling problem.

Besides its application to AMHS design for semiconductor manufacturing discussed previously, simulation has been also employed to study the operational aspects of MHS in these systems. Kuo [166] uses simulation to evaluate the performance of an overhead hoist transport system that provides the pod transport between process tools and stockers in an intrabay. Jimenez et al. [167] study the operational logic in an inter-bay AMHS in semiconductor wafer fabs. They propose several operation rules to minimize average lot-delivery time and use discrete event simulation to evaluate their performance. In order to prevent traffic jams in 300 mm semiconductor fabs, Wang and Chen [168] use a simulation method to analyze the performance of a heuristic dispatching rule of material handling equipment. Tyan et al. [169] propose an integrated simulation modeling approach to automate both the manufacturing process and the MHS. Through a case study, they examine the performance impact of the integrated tool and vehicle dispatching strategy based on cycle time, work-in-process, on-time delivery, and lot delivery time. Lin et al. [170] develop discrete-event simulation models to study connecting transport in a 300 mm wafer fab. They use a two-phase experimental approach to evaluate three connecting transports with regard to average travel time, throughput, and vehicle utilization.

An interesting trend in the application of simulation in operations planning and scheduling since the publication of the previous paper by Smith [33], is the extensive use of simulation to analyze the performance of newly proposed or existing scheduling rules. This growth implies that simulation is a very powerful tool to identify the most suitable dispatching rules and scheduling methods in order to improve the performance of manufacturing systems. Another interesting finding is the large number of simulation studies for operations planning and scheduling in semiconductor manufacturing systems. Successful application of discrete event simulation in semiconductor manufacturing has led to significant savings in terms of operational costs by improving the operation of these facilities which has further motivated researchers to study simulation applications in this context.

4.2. Maintenance operations planning and scheduling

While most of the operations planning and scheduling studies in the literature assume that machines are permanently available, in real life industrial settings machines can be unavailable for many reasons, including random breakdowns or scheduled Preventive Maintenance (PM) operations. Such disruptions in manufacturing operations significantly affect utilization and productivity. Maintenance operations, preventive and corrective maintenance (CM), are necessary to reduce the number of failures and fix existing mechanical problems. In other words, efficient PM and CM policies are crucial to maintain and improve overall operational reliability, utilization of the tools, and productivity of manufacturing systems. Many decision support tools have been proposed and applied in manufacturing systems for effective maintenance operations, see [171] for a review of such tools. In order to efficiently optimize or evaluate maintenance strategies, it is necessary to consider all of the factors that influence the performance of equipment. This can lead to very complex mathematical models that are difficult to develop and solve. This complexity and level of randomness has led researchers explore the potential use of simulation techniques to model and solve maintenance problems.

Perhaps the most important advantage of simulation in this context lies in its ability to simultaneously address maintenance, production, and inventory control problem which has been studied in several papers. Gharbi and Kenné [172] present a two-level hierarchical control model to deal with the production and preventive maintenance control problem for a multiple-machine manufacturing system. They combine analytical formalism with simulation-based statistical tools to determine the near-optimal values of the system's factors. Their approach involves a discrete-event simulation model consisting of several networks to describe different tasks in the system. Roux et al. [173] study the optimization of multi-component preventive maintenance problems. They develop a generic and easy-to-understand modeling tool for simulation in order to facilitate the optimization of production and maintenance. The proposed hybrid method consists of a simulation multi-model that combines several tools including discrete event simulation and timed petri-nets into a virtual laboratory environment (VLE) model. For similar studies, see [174,175]. Rezg et al. [176] propose an integrated method based on simulation and genetic algorithms for preventive maintenance and inventory control of a production line. They use simulation to model the behavior of the production system under various maintenance and inventory control strategies. In another study, Rezg et al. [177] describe a joint optimal inventory control and preventive maintenance strategy for a randomly failing production unit. They develop an approach based on simulation and experimental design to evaluate the average cost per time unit of the proposed strategy.

The results of our review suggests that simulation has been extensively used as an evaluation tool to analyze the performance of different maintenance policies and strategies in manufacturing systems. For a list of these studies, see [178–184]. As a decision making tool, Mjema [185] uses a simulation model to analyze the personnel capacity requirement in a maintenance department. Allaoui and Artiba [186] study the hybrid flow shop scheduling problem under maintenance constraints. They show how the integration of simulation and optimization can be used to optimize several objectives based on flow time and due date. Sharda and Bury [187] identify the impact of different failures on the overall production capabilities in a chemical plant using a discrete event simulation model. The simulation model helps understand key equipment components that contribute toward maximum production loss if failed.

A number of researches are devoted to the application of simulation techniques to PM scheduling in semiconductor manufacturing systems. Hernándndez et al. [188] describe the architecture and implementation of a preventive maintenance optimization software tool called PMOST for optimal scheduling of PM tasks in semiconductor manufacturing facilities. They conduct simulation case studies to demonstrate the improvement of PM tasks by PMOST. Yao et al. [189] propose a two-level hierarchical modeling framework based on mixed-integer programming for scheduling PM tasks. They conduct a simulation case study in order to evaluate the performance of the framework. Ramírez-Hernández and Fernandez [190] describe the application of a simulation-based approach to optimize PM scheduling decisions in semiconductor manufacturing systems. Simulation experiments show a significant reduction in average cycle time compared to a series of fixed baseline PM schedules.

4.3. Real-time control

Real-time control of manufacturing systems is a difficult problem due to the complexity and stochastic nature of these systems. Simulation has become an effective tool for real-time system control. However, the use of simulation as a basis for a real-time system controller is still a hard task due to response time, data collection and aggregation issues making it an emerging field of research within manufacturing systems. Castillo and Smith [32] provide a survey of modeling methodologies for manufacturing cell control. They classify formal models of manufacturing cells as either logical or timed and discuss that discrete event simulation is the largest class of timed models.

The development of simulation-based control systems and integration of discrete event simulation with other tools and techniques for manufacturing system control has been investigated in several studies. Iassinovski et al. [191] describe the structure of a distributed decision-making system for process control in complex discrete systems which incorporates on-line simulations, state-graph search, expert systems, and other methods for decision making. Metan et al. [192] develop a new scheduling system for selecting dispatching rules in real time using simulation, data mining, and statistical process control charts. By integrating vector ordinal optimization (VOO) and response surface methodology, Hu and Zhang [193] propose a scheduling method for real-time control of semiconductor fabs. They also compare the performance of the proposed VOO-based simulation approach with traditional simulation. Zeng et al. [194] propose an operator allocation model consisting of an optimization tool based on Pareto utility discrete differential evolution and embedded discrete event simulation to analyze dynamic behaviors and balance control of hybrid assembly lines. Jönsson et al. [195] describe a structure for real-time simulation of CNC machine tools which incorporates a control system, simulation models of the machine, and a virtual reality model. Son et al. [196] provide the architecture, implementation, and the integration of all the components of a simulation-based shop floor control system. In their approach, discrete event simulation is used both as an evaluation tool and a task generator that drives shop floor operations in real time. For a list of similar studies, see [197–202].

Performance analysis of newly proposed or exiting control schemes and methodologies has been reported in several papers. Brennan [31] provides a background on the work in distributed intelligent control and the application of these techniques to the physical level of control where real-time constraints are prevalent. They also highlight the recent research on simulation of real-time distributed control systems as a verification and validation tool. Different control schemes for logistic systems including AMHS and AGV systems have been evaluated through simulation. Versteegt and Verbraeck [203] describe the role that simulation can play to evaluate fully automated logistic systems and their control systems. They use three different simulation packages namely Simple++, AutoMod, and Arena in their approach. Berman and Edan [204] develop a control methodology for decentralized autonomous AGV systems. The production system is then simulated to evaluate the AGV system management methodology. They implement the methodology in a computer-integrated manufacturing environment. For a list of similar studies, see Scholz-Reiter et al. [205], Wang and Lin [206], Driessel and Mönch [207], Venkatesh and Smith [208]. Several other studies use simulation to assess the performance of real-time control systems in assembly lines Gong et al. [209], Wu et al. [210], flow shops [211,212], and job shops [213], and semiconductor manufacturing [214]. For related problems on the application of simulation as an evaluation tool for manufacturing control, see [215–217].

Perhaps the most fertile area for the application of simulation in manufacturing system control is the control of flexible manufacturing systems. A review of simulation-based Intelligent Decision Support Systems (IDSS) for FMS real-time control is provided by Mahdavi and Shirazi [19]. Shirazi et al. [218] present an intelligent real-time controller for flexible manufacturing systems where simulation is used to train the IDSS and choose appropriate control rule in real-time. Mahdavi et al. [219] describe a controller design approach based on real-time discrete-event simulation and a rule-based DSS for controlling stochastic flexible job shop manufacturing systems. Qiao et al. [220] propose a data-driven design and simulation system to support flexible manufacturing. The simulation model can be quickly modified to adjust manufacturing capabilities and production processes, reconfigure layout, and reassign resources in response to demand change and can be easily used for manufacturing control. Considering the objective of reducing congestion in FMS, Souier et al. [221] present a simulation study on the performance of different metaheuristics namely ant colony optimization, GA, simulated annealing, tabu search, particle swarm optimization and electromagnetism-like methods for real time rescheduling. Shirazi et al. [222] develop a centralized simulation controller with a real-time discrete event simulator equipped with a concurrent bilateral mechanism for simulation-based optimization. For similar studies, see [223,224].

Brennan and William [225] evaluate the performance of alternative multi-agent approaches to manufacturing planning and control. In their modular experimental model, the multi-agent control module is linked to a discrete event simulation model of a benchmark manufacturing system. In another paper, [226] propose a coordination approach for a multi-agent architecture to deal with real-time scheduling of cellular manufacturing systems and compare the performance of this approach with another method based on the workload index. Deadlock detection and resolution is another area within FMS control that has been studied in a few papers [227,228]. As an evaluation tool, simulation has been also used to assess the performance of real-time tool selection rules and methods in FMSs [229–231]. other applications of simulation for evaluation of control strategies are provided in [232,233]. A number of papers study the impact of information delay on FMS scheduling. Caprihan et al. [234] define three key delay modes as information-transfer delay, decision-implementation delay, and status-review delay. Moreover, they develop simulation models for each mode of information delay to study their impact on sequencing decisions for the machine. Caprihan and Wadhwa [235] discuss that the lack of an integrated control mechanism within semi-automated flexible manufacturing systems causes delays in the availability of shop status information. In addition, they describe the modes of information delay and their impact on the performance of the system through simulation studies. Caprihan et al. [236] introduce a dispatching strategy based on fuzzy logic to cope with status review information delays within FMSs. They used simulation to investigate the performance of the proposed approach.

4.4. Operating policies

As discussed by Smith [33], the distinction between the operating policies and real-time control categories is that the work belonging to the former class analyzes steady-state performance, while the real-time control deals with the analysis of different operating strategies as a real-time dynamic decision making problem.

Using simulation experiments and a multi-criteria decision making method, Lu et al. [237] aim to find the optimum junction point of push and pull production control policies with the objective to maximize the throughput and minimize the inventory levels. Sabuncuoglu and Kizilisik [238] propose several reactive scheduling policies and use simulation to test their performance under various processing time variations and machine breakdowns. Furthermore, they compare offline and online scheduling schemes by extensive simulation experiments. Gupta and Sivakumar [239] compare the steady-state performance of a look-ahead batch scheduling control policy to the steady state performance of the theoretically optimal control strategy. Simulation results indicate that the look-ahead strategy improves the performance of the system under various conditions of the system. Through a scalable production planning simulation model, Felberbauer et al. [240] study the performance of two different machine allocation (i.e., segmentation) policies in a combined MRP and Kanban production system. Mehra et al. [241] use simulation to compare different lot/batch sizes with regard to five performance measures. The simulation results indicate that lot/batch size reductions can benefit both continuous and discrete manufacturing systems. A simulation environment is developed by Renna and Ambrico [242] to compare the performance of three cell-loading policies under fluctuations of volume and product mix in a classical cellular manufacturing system. Gilland [243] use simulation to evaluate alternative policies for releasing material into a manufacturing cell in order to maximize the output rate for a given level of work-in-process inventory. Pearn et al. [244] present a due-date assignment model in order to satisfy certain on-time-delivery rate. They use simulation to demonstrate the applicability of the model in real-world wafer fabrication by getting the steady-state results for different product mixes.

5. Simulation language/package development

Recently, numerous research publications have addressed the development of simulation tools/packages/frameworks with the application to manufacturing systems design and operations. These publications are classified under three basic categories: generic simulation models; simulation/modeling methods and frameworks; and simulation metamodeling/optimization methods. The first two subclasses are similar to those adopted in Smith [33]. However, due to the large number of articles addressing these areas, they are discussed as two distinct subclasses in the current paper. The third subclass is a new category that has emerged over the last twelve years. The following sections describe the published research in each of these areas.

5.1. Generic simulation models

While most of the simulation studies in the literature address a narrow set of manufacturing problems or single-use applications of discrete event simulation, a number of authors describe the issues associated with the development of generic simulation models that are reusable for wider applications. This section describes the published research in this area.

Fowler and Rose [245] describe challenges in modeling and simulation of manufacturing systems. They discuss the need for general-purpose architectures for simulation reuse and plug-and-play interoperability as a grand challenge. McLean and Shao [246] discuss the possibility that different simulation analysts obtain different results and reach different conclusions from their case studies. They describe the standardization of case study methodology and development of generic simulation case studies that can produce repeatable results. Akiya et al. [247] propose a framework for building generic simulation models for non-steady process networks. The framework is based on a rule-based queue and resource-task network representation and can be implemented in any simulation software. McLean et al. [248] describe the work done at the National Institute of Standards and Technology (NIST) to develop a generic machine shop simulator. The data-driven simulator can be used in a large number of machine shops. Son et al. [249] describe the use of formal neutral models of simulation components proposed by NIST. They further discuss that libraries of formal neutral models of simulation components would simplify the generation of simulation models and enable reuse of existing models. They also present a discrete-event simulation of a job shop system using a collection of these components.

Angelidis et al. [250] introduce a generic simulator incorporating realistic schedules, priority rules, and resource restrictions designed specifically for the simulation of complex assembly lines. In another paper, Kibira and McLean [251] describe the development of a generic simulation model of an assembly plant to be used in distributed integrated manufacturing simulations for automotive manufacturing. Moreover, increasing the versatility of the model, running on neutral data, and integration with supply chain simulation are discussed as future research opportunities. Lee et al. [252] discuss the benefits of standard representations for information entities common to manufacturing simulation in reducing the cost of simulation model construction and data exchange between simulation and other applications. In order to make simulation techniques more affordable and accessible to a wide range of manufacturing systems, they present an overview of a standardized, computer-interpretable representation called Core Manufacturing Simulation Data (CMSD). In their work, they also illustrate the use of CMSD to integrate real-world manufacturing applications through case studies. By simplifying a typical TFT-LCD fab into a homogeneous job shop consisting of only bi-inline cells, Song et al. [253] propose and verify an event graph model of the fab that can be considered as a starting point for developing simulators for performance analysis in such environments. Garg et al. [254] propose generic interface specifications to enable interoperability among distributed discrete-event simulation models.

5.2. Simulation/modeling methods, frameworks, software tools

Simulation-oriented issues of *ORMS Today* magazines provides biennial lists of commercial simulation tools/packages/languages and give general descriptions of each product's capability, special features, and usage including but not limited to the user interface, experimental design and analysis capabilities, and animation features. Due to these differences, no single simulation package is suitable for addressing all types of manufacturing problems. Therefore, it is necessary to choose the most suitable simulation software for the specific application under study. To address this problem, Cochran and Chen [255] develop a fuzzy set approach for multi-criteria selection of simulation software to analyze production systems.

Buss [256] demonstrates the use of an open source package written in Java called Simkit to create discrete event simulation models using a component framework. Kim and Jae [257] present an object-oriented simulation modeling environment called AgvTalk to provide flexible modeling capabilities for the simulation of AGV systems. The simplicity of defining and changing system requirements and specifications is the main modeling advantage of AgvTalk. Wainer [258] presents the features of a toolkit called CD++for modeling and simulation based on the Discrete Event Systems (DEVS) formalism. In a similar study, D'Abreu and Wainer [259] present the M/CD++as a tool for modeling and simulation of continuous/hybrid systems. Zülch et al. [260] investigate the integration of various detailed submodels into an overall global model of production systems using a new tool called OSim. They give a practical example for application of this hierarchical approach in an aluminum factory. Gan et al. [261] present an approach to interoperation of two commercial simulation packages – AutoMod and AutoSched – in order to include an AMHS model in the manufacturing process model.

Several studies in the literature provide general simulation modeling methods and frameworks with the application to a variety of manufacturing environments. Kim et al. [262] propose a generic simulation modeling framework for reducing the time required for building simulation models for semiconductor manufacturing systems. A similar study is carried out by Wy et al. [263]. Gregg et al. [264] present an approach called Lean+Process Analysis Simulation (LPAS+) which is based on a database-driven simulation architecture that has been successfully applied to model aircraft production flows and analysis of labor and equipment requirements at Boeing. Mclean et al. [265] present an architecture for integrating distributed manufacturing simulation systems with each other and with other manufacturing software applications and data repositories. Zhai et al. [266] combine Computer Aided Design (CAD), Virtual Reality (VR), and discrete event simulation techniques to present a structure to support virtual factory engineering.

Tavakoli et al. [267] present a generic framework for real-time discrete event simulation modeling with applications to both manufacturing and healthcare systems. Haas [268] presents the elements of a steady-state simulation theory for the use of Stochastic Petri Nets (SPNs) in discrete-event simulation. Zhao et al. [269] introduce an efficient event-scheduling simulation method with a two-level framework for modeling and analysis of a general assembly systems including a MHS. Roeder et al. [270] describe a resource-driven simulation approach to modeling semiconductor wafer fabs. They study both resource-driven and job-driven simulations and show that some aspects of the fab can be modeled more accurately using the resource-driven model, while others are more accurately modeled in a job-driven simulation approach. Porzucek et al. [271] use an analytical performance prediction approach to improve the performance of discrete event simulation. They evaluated their method based on an industrial case study.

Venkateswaran and Son [272] develop a hybrid simulation-based hierarchical production planning architecture consisting of system dynamics and discrete event simulation. In their proposed architecture, discrete event simulation is used for the shop-level scheduling while SD is used for enterprise-level planning. For a similar research, see Venkateswaran et al. [273]. In another study, Rabelo et al. [274] propose a hybrid approach integrating discrete-event models with system dynamic models to evaluate production decisions in manufacturing enterprises. Sanchez et al. [275] use a methodology called frequency domain experimentation to gain better insight into the behavior of production systems when simulation output stream exhibits high positive autocorrelation. Koo et al. [276] verify a Programmable Logic Controller (PLC) through modeling and simulation using a framework of virtual plant models and applied their framework to a car assembly line. Nazzal et al. [277] present a framework consisting of simulation modeling, design of experiments, statistical analysis, and economic justification tools for strategic capacity expansion of production equipment in wafer fabrication facilities.

In the object-oriented simulation context, Anglani et al. [278] present a procedure to develop simulation models based on the UML tools with the goal of improving the efficiency of a commercial simulation software through adding fundamental object-oriented features to it. Huang et al. [279] explore the use of Systems Modeling Language (SysML) as an extension of Unified Modeling Language (UML) to support the automatic generation of object-oriented simulation models. In a case study, they present the essential SysML model of a flowshop system. Park [280] proposes an object-oriented methodology to create a virtual FMS model.

5.3. Simulation metamodeling and optimization methods

This section presents research publications describing simulation metamodeling and optimization techniques. As opposed to theoretical aspects and technical details of these techniques, our focus here is specifically on applications in manufacturing system design and operation. For a list of review papers on simulation metamodeling and optimization, see [281–284].

5.3.1. Simulation metamodeling

A meta-model, or response surface, is able to approximate the unknown input-output function implied by the underlying simulation to provide fast and robust decision support aids to improve the overall decision-making process. Artificial Neural Networks (ANNs) are commonly used for simulation metamodeling in the literature. Fonseca et al. [285] provide general guidelines for the development of ANN-based simulation metamodels. They apply the guidelines in the development of two ANNs to estimate the manufacturing lead times in a job shop setting. In a similar study, Fonseca and Navaresse [286] prove that ANNs are viable tools for stochastic simulation metamodeling through an example of a job shop system. Laguna and Martí [287] propose a training procedure for neural networks and use data from the simulation of a job shop to compare the performance of the proposed method with other approaches. Can and Heavey [288] use three common industrial systems, namely an AMHS in a semiconductor fab, a production line, and an inventory problem to compare genetic programming and artificial neural networks as metamodels for discrete event simulation models. For a related study on simulation metamodeling for manufacturing systems, see [289].

Guh et al. [290] seek to develop a real-time controller system based on self-organizing map neural network where a simulation-based example generation mechanism is used to train the metamodel. Yang [291] develops an experiment design method to collect simulation data for efficient estimation of the neural network models in order to generate cycle time-throughput time

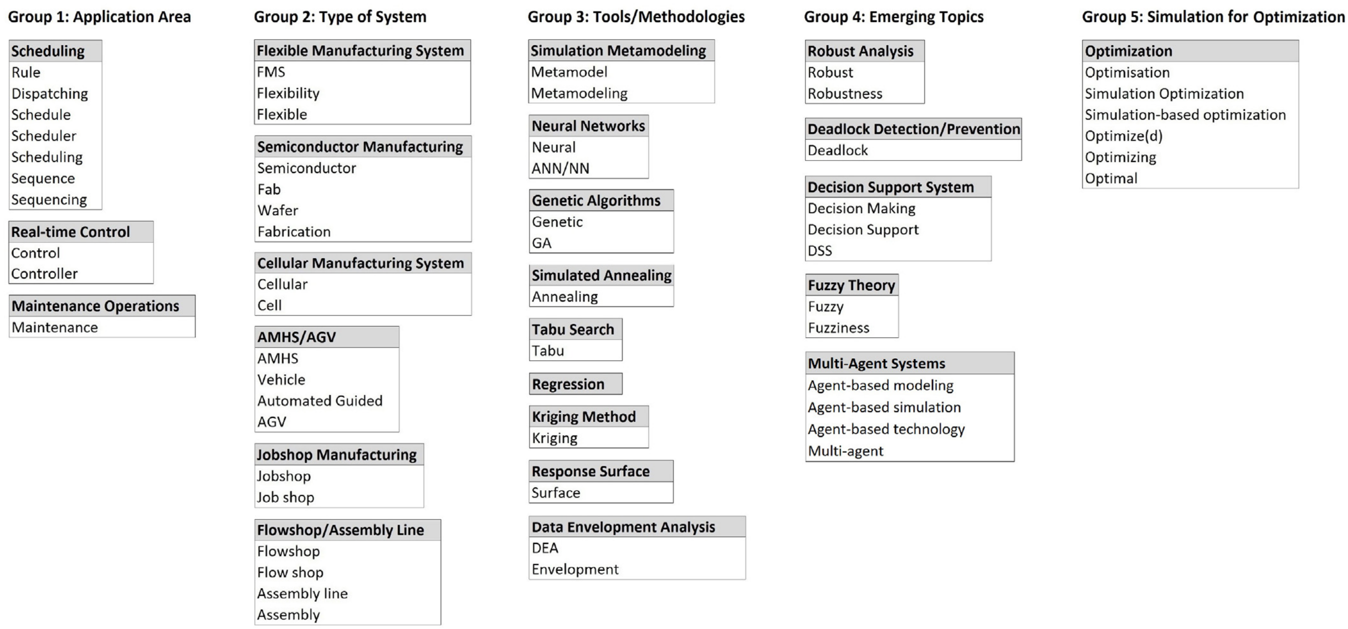

Fig. 1. Key terms used to form clusters to conduct literature analysis.

profiles for manufacturing systems. Azadeh et al. [292] propose an algorithm based on computer simulation and ANN to select the optimal dispatching rules in stochastic job shops with the objective of minimizing the makespan. The significant contribution of their study lies in finding the optimal dispatching rule combination while considering non-identical dispatching rules for machines under normal, exponential, and uniform processing time distributions. ANN metamodels for bi-criteria assembly flow shop scheduling [293] and AMHS dispatching in semiconductor fabs [294] have also been studied.

Kleijnen and van Beers [295] investigates the use of Kriging metamodling in random simulation through examples of M/M/1 systems that can be applied in manufacturing settings. In another study, van Beers and Kleijnen [296] propose a Kriging metamodling method based on customized sequential designs for discrete event simulation. They tested the method using a simulation model of an M/M/1 queueing system. Joseph and Sridharan [297] develop a simulation-based metamodel to analyze the performance of a typical FMS under different levels of routing and sequencing flexibility and four different dispatching rules.

5.3.2. Simulation for optimization

In the context of simulation optimization, Bettonvil et al. [298] present a simulation-based optimization approach with multiple outputs and study the robustness of their procedure through several examples including optimization of an integrated production-inventory simulation model. Hong and Nelson [299] propose an optimization algorithm for discrete event simulation, called COMPASS. An assemble-to-order system is studied as a numerical example. In another study, Xu et al. [300] investigate the Industrial Strength COMPASS (ISC) as an optimization-via-simulation framework and compare it to the commercial optimization-via-simulation package OptQuest on five test problems including a production line problem. Ng et al. [301] introduce an Internet-based platform called FACTS that integrates automatic model generation and optimization engines to facilitate model development and optimal decision making. In the FACTS server, various optimization tools and ANN-based metamodels are made available to the user. Pichitlamken and Nelson [302] propose an optimization-via-simulation algorithm where discrete event simulation is used to measure the performance of the system. They use the proposed approach to maximize the average output of a flow line by finding the best buffer allocation and service rates.

Yang and Chou [303] develop a multiple-attribute decision-making method to solve the multi-response simulation-optimization problem and apply the method to a case study from an integrated-circuit packaging company. Through a case study, Mahfouz et al. [304] integrate simulation with optimization techniques to evaluate the implementation of lean principles in small and medium enterprises (SMEs) with regards to three performance measures, namely cycle time, WIP, and workforce utilization. Eklin et al. [305] integrate simulation and optimization to develop a cost estimation model that considers limited capacity in a stochastic environment. They show the advantage of the proposed heuristic over an existing deterministic approach through an example of a manufacturing system. Melouk et al. [306] propose a simulation optimization-based decision support system for steel manufacturing where an optimizer, OptQuest™, sends potentially beneficial process modifications a simulation model to investigate their performance of the system. Matta [307] presents mathematical programming representations for simulation optimization of buffer allocation in flow lines. For related studies in semiconductor and cellular manufacturing, see Pfeffer et al. [308], and Montevechi et al. [309], respectively.

Integration of simulation with evolutionary and metaheuristic search methods for optimization purposes have been addressed in a number of papers. Piera et al. [310] describe a new approach to integrate simulation methods with search methods for optimization of complex logistic or manufacturing systems. The application of such approaches have been illustrated in case studies of an engine manufacturing line [311], flow shop [312], job shop [313], dedicated remanufacturing [314], FMS [315], parallel machine scheduling [316], and multi-constant work-in-process problem [317].

6. Detailed analysis of the literature

In this section, we provide a detailed analysis of the literature in order to identify literature trends and emerging research topics on simulation applications in manufacturing. Although our literature review reveals a general shift from design to operational aspects,

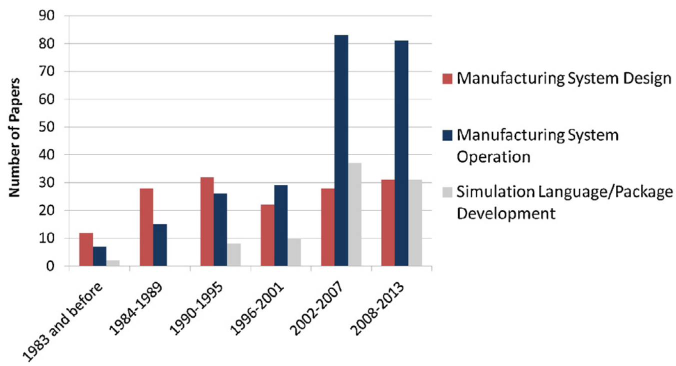

Fig. 2. Number of papers for application areas, by year.

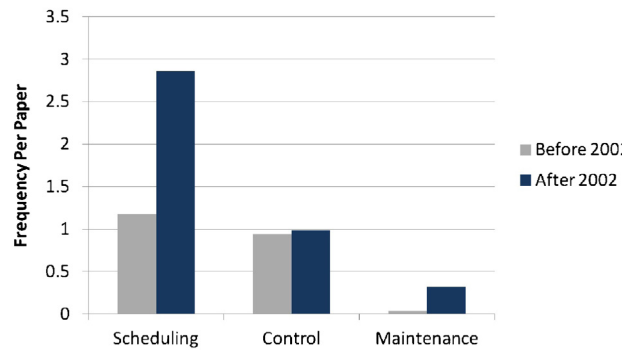

Fig. 3. Text mining results on scheduling, control, and maintenance.

more analysis is provided here by comparing the results of the current paper with the preceding paper by Smith [33] to identify when these shifts have occurred and how the primary application areas have evolved with time. We also employ a novel text mining approach to extract more information on different facets of the literature in order to justify our findings and reveal key differences between the traditional and modern practice of discrete event simulation in manufacturing.

The text mining procedure can be summarized as follows. The frequency of all phrases with up to three words are extracted from the title, keywords, and abstract of the 475 research articles reviewed in the two survey papers. The important key words are then identified by sorting the results according to their frequency of occurrence. In order to provide a common ground for comparison between the state of the literature before and after 2002, the frequencies are divided by the total number of papers in the pool. Finally, related words are identified to form clusters in order to extract meaningful information. More specifically, we group our text mining analysis into five categories of application area, type of system, tools/methodologies, emerging topics, and simulation for optimization. Fig. 1 presents the key terms used to form the main clusters that are used in the analysis under each group. The text mining process is performed using the RapidMiner® open-source data mining package.

Our first analysis aims to illustrate the general trends observed in the literature during the past 50-plus years as shown in Fig. 2. We use the number of reviewed papers to reveal these trends and use text mining results to support our analysis which can be summarized as follows:

- Perhaps the most important finding is the significant increase in the total number of publications which indicates the growing trend in the application of simulation to different problems in the manufacturing realm. Increase in computational power and computer memory, incorporation of optimization algorithms into simulation software packages, incorporation of variance reduction, and other efficiency enhancement techniques are identified as some of the contributing factors to this growth. Moreover, advancements in verification and validation techniques along with the successful adoption and application of simulation by more and more manufacturing firms has certainly increased the credibility of this tool among researchers and practitioners resulting in this growing interest.
- The results support our claim that initially, simulation was mostly used to address long-term design problems where computational time does not play a substantial role. The figure confirms our previous finding on the shift in the the application of simulation from design to operational aspects. The results indicate a surge in the number of papers under the manufacturing system operation class starting from mid 1990s. However, the major surge in this application area occurred in early 2000s. This finding is consistent with the text mining results that show a significant increase in the use of terms related to scheduling and maintenance since 2002 (Fig. 3). Although these findings justify the emergence of maintenance operations planning and scheduling as a new category in the literature, a huge gap exists between these application areas and far more attention needs to be devoted to maintenance operations. Moreover, the results of text mining is also inline with our finding that real-time control has maintained itself as a fertile area for simulation applications. In general, the growth in manufacturing system operation can be mainly attributed to increased computation power of computers enabling manufacturers to use simulation for short-term decision making problems such as those encountered in scheduling, real-time control, and maintenance.
- Fig. 2 illustrates a decline in the number of design-related applications starting in mid 1990s as operational aspects became the foci of the majority of simulation studies. However, since 2002, however, a slow yet growing trend can be observed in the application of simulation in manufacturing system design. Further analysis indicates that nearly two-thirds of recent publications in this class deal with material handling, flexible and cellular manufacturing systems (40 out of 58 papers). These papers mainly discuss integration of simulation with statistical or economical tools as well as simulation metamodeling and optimization techniques to solve design problems. Moreover, it is found that a new stream of approaches to FMS and CMS design are recently pursued that view the entire manufacturing process as a whole by integrating design considerations with production planning and scheduling.
- Fig. 2 also indicates a significant growth in the number of articles dealing with the third main category in recent years. Two possible reasons have been identified for this surge. The first reason lies in the increased interest in simulation metamodeling and optimization. Although simulation was initially used as a descriptive tool mainly for prediction and performance analysis, more recently, researchers have shown a significant interest in merging optimization and simulation in order to find the optimal or near-optimal design and/or operating policies for manufacturing systems. The fact that most discrete event simulation packages we use today include some sort of optimization tool is the result of the rapid growth in research on simulation-based optimization. Our text mining results also support these findings by comparing the use of optimization-related terms as well as the integration of simulation with other tools for metamodeling or output analysis (Figs. 4 and 5). These observations confirm the expansion of the previous classification to include the new category of simulation metamodling and optimization.

Fig. 6 illustrates the amount of work that has been carried out on different types of systems. The results suggest that simulation is

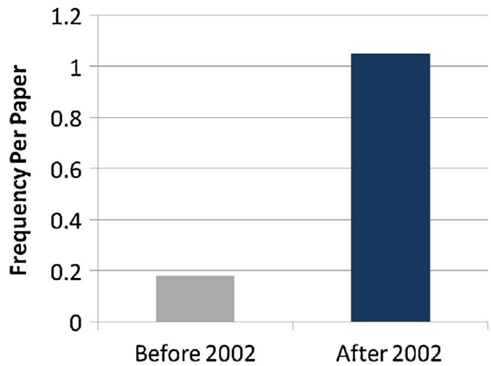

Fig. 4. Text mining results on the frequency of optimization-related terms.

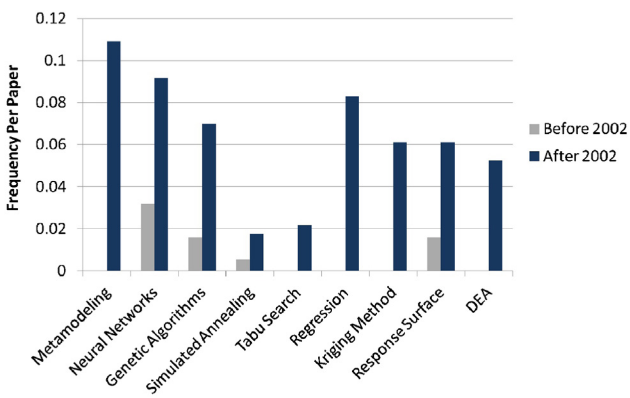

Fig. 5. Text mining results on simulation integration with other tools.

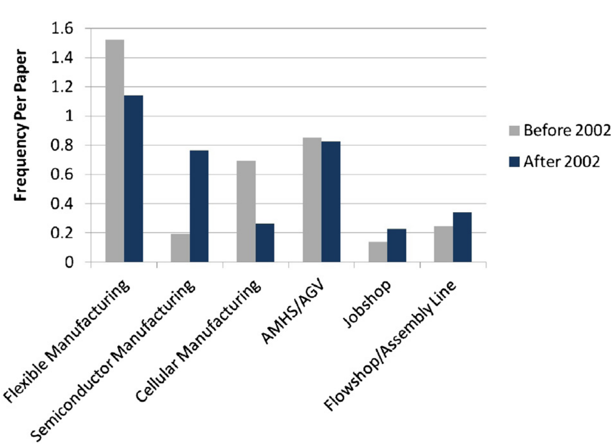

Fig. 6. Text mining results on different system types.

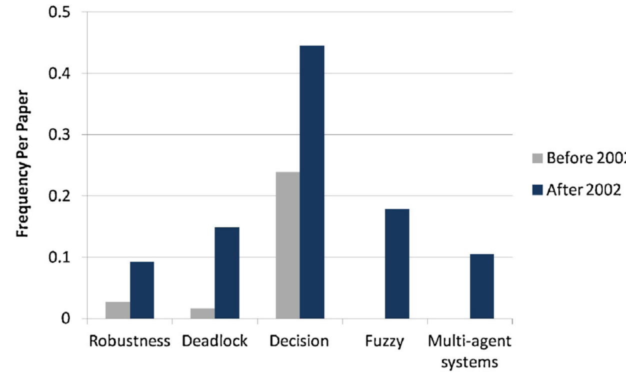

Fig. 7. Text mining results on robustness, handling deadlocks, decision making, fuzzy logic, and multi-agent systems.

extensively used to study flexible manufacturing systems and automated material handling systems. However, job shops and flow shops have received relatively less attention. A potential reason for this difference could be the high levels of complexity within FMS and AMHS which makes the analysis of these systems beyond the reach of analytical methods while many problems within the realm of traditional job shop or flow shop are farily tractable using mathematical or analytical techniques. It is worth noting that the decline in FMS-related applications observed in Fig. 6 is mostly due to the decreased interest in traditional FMS design problems. In fact, our literature review suggests that scheduling and real-time control of flexible manufacturing systems were addressed in 32 papers which indicates a significant growth. On the other hand, only 9 papers have addressed FMS design problems, an area that used to receive a tremendous amount of attention before 2002 (including more than 29 papers as reported by Smith [33]). The inherent complexity of these systems has attracted researchers to use simulation as an analysis tool for studying operational areas of FMS. This can be viewed as the main reason to the shift from FMS design to FMS scheduling and real-time control. Furthermore, many of the cited publications under this domain in the earlier survey describe the development of new simulation packages/platforms specifically designed for simulating flexible manufacturing systems. The results of the current paper suggest that this research area is receiving significantly less attention in the recent literature as it became more mature.

Our review suggests a significant increase in the application of simulation to various aspects of semiconductor manufacturing, including but not limited to material handling system design, operation planning and scheduling, and maintenance operations in these environments. These studies constitute 16% of the reviewed literature published after 2002 which indicates a significant growth as also shown in Fig. 6. Automated material handling and AGV systems maintain their popularity for simulation applications. Based on the results of the current paper, AGV systems are specifically studied in 26 papers which indicates the ability of simulation in addressing different design, control, and decision making problems associated with these complex systems. Finally, our review suggests a decreasing trend in the application of simulation in both design and operational aspects of cellular manufacturing systems which is also highly consistent with the text mining results.

Several other insights have been derived from the the text mining results. The use of simulation as a decision making tool during the past twelve years is salient from our literature review which is consistent with the text mining results as illustrated in Fig. 7. Development of robust simulation-based tools for operational decision support seems to be evolving as a promising path for future endeavors. The growing interest in the use of simulation for handling deadlocks is another interesting finding which can be attributed to the fact that other deadlock detection algorithms mainly work for simple networks that are analytically tractable. Application of fuzzy

Table 4
Comparison of different tools and techniques used in the literature.

Tool/technique	Number of references	**List of related references**
Neural networks	12	[127,285–294,301]
Genetic algorithms	9	[36,46,71,128,142,176,221,288,315]
Simulated annealing	1	[221]
Tabu search	3	[129,221,312]
Kriging method	3	[295–297]
Data envelopment analysis	3	[43,70,72]
Fuzzy logic	8	[43,70,83,111,127,153,236,255]
Multi-agent systems	7	[52,87,88,100,209,225,226]

set theory in simulation studies of manufacturing systems is found as an emerging topic that provides a great deal of opportunities for future research. Finally, as a relatively new field, multi-agent systems and their applications in manufacturing systems have been identified as another emerging topic. Table 4 compares the application of the tools discussed above along with a list of related references.

7. Conclusions

This survey presents a review of 290 papers published from 2002 to mid 2013 on the application of discrete event simulation in manufacturing, which suggests that, on average, about 25 articles per year have been added to the literature. This average number was less than 6 papers per year according to Smith [33] who surveyed the literature in over 34 years from 1969 to 2002. This shows a significant growth in the annual published research on discrete event simulation for manufacturing system design and operation. The current review aims at identifying new application areas and extending the earlier classification schemes. Moreover, using the insights obtained from reviewing a large pool of related articles as well as novel data mining approaches, the paper uncovers the trends in the literature since its very early years and highlights the emerging topics.

In this survey, the literature is classified into three primary classes. Most of the recent publications address manufacturing system operation applications, i.e. roughly 56%. Almost 24% of the papers fall into the simulation language/package development class. Finally, the remaining 20% of the reviewed papers are categorized under the manufacturing system design class. In the survey by Smith [33], these results were 41%, 10%, and 49%, respectively. The results suggest that there has been a shift in the literature from manufacturing system design to manufacturing system operation. Manufacturing operations planning and scheduling is found to be the most popular application area for discrete event simulation. This subclass alone contains more papers than the total number of papers under manufacturing system design. Real-time control is identified as the next leading application area. Moreover, the use of simulation for manufacturing system operation has further expanded to include the new subclass of maintenance operations planning and scheduling.

Another new category that has been identified in this paper is simulation optimization and metamodeling which offers a broad range of future research opportunities. Development of new and more robust optimization tools and incorporating them into commercial simulation software would be beneficial to enhance the performance of these packages and broaden their application in manufacturing systems. Future research could also involve development of new simulation metamodeling approaches that could provide more robust and faster decision support aid. Comprehensive and formal comparative analysis of metamodel-based simulation optimization techniques can also help researchers and practitioners conduct more successful work in the future.

The application of simulation in manufacturing system design and operation is expected to continue growing and evolving in the future as the manufacturing sector remains an important part of the global economy and becomes more competitive. There is a need for more efficient techniques to deal with the growing complexity of manufacturing operations. The rising of hybrid approaches, where simulation is coupled with one or more techniques, is salient in the results of our analysis. Integration of simulation with artificial neural networks and genetic algorithms show a significant increase over the past twelve years. Integration with other techniques namely Kriging method, data envelopment analysis, fuzzy logic, and multi-agent systems are also found as emerging areas that had been previously ignored in the literature. The adoption of such approaches is likely to grow as manufacturing researchers and practitioners become aware of their advantages over traditional simulation. Finally, although our review highlights a few studies on the application of discrete event simulation for long-term planning, far more attention needs to be given to the integration of simulation with upper levels of management and enterprise control systems in order to increase stakeholder engagement.

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