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Overview of simulation tools for computer-aided production engineering

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Abstract

Due to increasing demands on efficiency, quality, and flexibility in manufacturing companies today, it has become very important to structure the development process of manufacturing systems. This process, for example, could be supported by using models, architectures, and simulation tools. The purpose of this paper is to outline the background to simulation in manufacturing engineering and give an overview of simulation software tools used for Computer-Aided Production Engineering. The paper discusses the features that are most important to consider before investing in such tools. A comprehensive overview of commercial simulation software tools is presented and future areas for research and development are discussed. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Manufacturing simulation; Computer-aided production engineering

1. Introduction

Customer and market demands for new products with high quality and low price put much pressure on increasing the efficiency and quality at all stages in the life-cycle of manufacturing systems ((re-) design, implementation, and operation). To increase efficiency, there is a need to minimise the time and cost for development and operation of a manufacturing system. Therefore, it becomes more and more important to be able to analyse and test a manufacturing system before a large investment.

Shorter product life-cycles require the manufacturing system to be highly flexible to be able to meet frequent changes. It is not sufficient anymore to meet changes when they occur. The changes must be predicted. Shorter product life-cycles also constrains the time available for developing new manufacturing systems, or for reconfiguring of old manufacturing systems.

To be able to consistently handle the demand for increased efficiency, quality, and flexibility and reduced development times, it is becoming increasingly important to structure the work using a *methodology* (strategy). One important aspect of such a methodology is the use of *models and architectures* that provide an abstract, simplified representation of reality [1]. Another important part of a methodology is the use of computer aids. Product design has been supported by computer aids like CAD/CAM for many years. In the same way, manufacturing equipment has a high level of automation

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and computer support. However, the computer-based support in the production engineering area is still quite low (see Fig. 1). There is a promising technology that aims at solving this problem: *Computer-Aided Production Engineering, CAPE.*

The CAPE technology makes it possible to bridge the gap between product design and automated manufacturing by providing computerised tools for production and process design (see Fig. 1). Simulation software tools are the computerised tools that represent the core in CAPE. CAPE makes *Concurrent Engineering* possible by emphasising parallel product and process development work. Planning of the production can be verified in the computer and knowledge can be gained before investment.

The objectives of the research presented in this paper are to give an overview of the background for simulation in manufacturing engineering and simulation software tools used for supporting the development process of manufacturing systems. The second objective is the principal focus of this paper, aiming at discussing future trends and finding research and development areas.

There are many different simulation software tools available in the market today. The focus is on major commercial simulation software tools used for specific applications in *manufacturing*. All these tools have interactive graphical interface and use real-time graphical animation to depict the performance of the system.

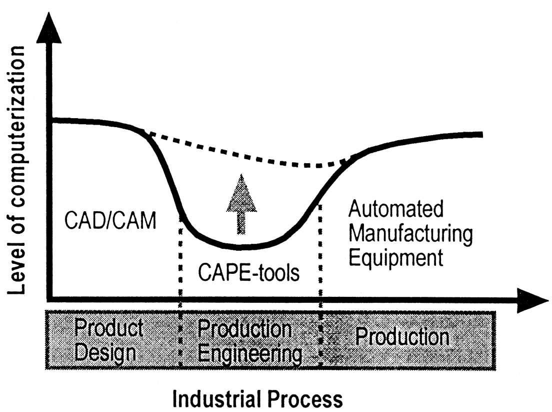

Fig. 1. CAPE Tools: bridging the gap between product design and production [2].

Simulation tools *not* considered in this paper are: pure Computer Aided Robotics tools such as Rotsy (Motoman), Business Process Re-engineering tools, IDEF-like modelling tools, Virtual Reality tools, Numerical simulation tools (Matlab, etc.) and Pure simulation languages such as SLAM, Siman, or SimScript.

The rest of the paper is organised as follows: Section 2 introduces the relevance of simulation in manufacturing engineering. It is supported by the literature survey and our own experience in this field. Sections 3 and 4 details the available simulation software tools. The discussions in both these sections are supported by the relevant literature survey, our own experience and informal discussions with the vendors and end users.

2. Introduction to simulation

The term *simulation* can be defined in several ways. However, two definitions that fit well for our purpose of defining simulation in manufacturing are:

Simulation is the art and science of creating a representation of a process or system for the purpose of experimentation and evaluation [3].

. . . the process of designing a model of a real system and conducting experiments with this model for the purpose of understanding the behaviour of the system and/or evaluating various strategies for operating the system [4].

The thinking behind both definitions is similar: building a model of a real system (or a system-to-be), conducting experiments with this model, and creating some kind of output result for decision making and implementation support.

Why should simulation be used? Simulation experiments can be conducted for several reasons, but they actually have the same primary purpose; all simulations are conducted to be able to make better decisions [5]. Improved decision making leads to increased efficiency and reduced costs—two principal goals of any company. In other words, the main reason for using simulations is to support *decision making*. Some examples of what simulation can be

used for are: prediction of system performance, evaluation of a certain feature in the system, comparison between several alternatives, gaining knowledge of the system at different life-cycle phases, problem detection, and presentation of predicted results.

2.1. Benefits and limitations of simulation

Listed in Table 1 are a few examples of benefits and limitations with simulation.

2.2. Steps in a simulation project

To structure work using a methodology is becoming increasingly important as systems become more complex. Simulation methodologies are developed by Musselman [8], Robinson and Bhatia [7], and Withers et al. [9]. Withers describes a very comprehensive simulation methodology suggesting five basic steps to go through in a simulation project:

1. understand system and customer,
2. produce conceptual model,
3. produce model,
4. use model, and
5. assess model use. Each one of the steps are then decomposed and described in detail.

However, using a methodology alone doesn't solve all problems in a simulation project. Three important things that are often overlooked are: (i) the simulation project team should involve a broad spectrum of employees, from shop-floor operators to key decision makers, (ii) the simulation analysts must have good knowledge of simulation methodology and programming [6], and (iii) selection of the right simulation software tools.

2.3. Manufacturing simulation

There is a distinction between two types of simulations in Computer-Aided Production Engineering:

- Discrete event simulation (DES)
- Geometric simulation (GS)

2.3.1. Discrete event simulation

Most commercial simulation software tools for Computer-Aided Production Engineering are discrete event simulators that simulate the behaviour of entities when an event occurs at a distinct point of time [10]. Entities are the components of a system, described by variables. The instants in time when variables change are called events. Occurring events drive the simulation and the simulation clock. Between events nothing happens. Thus, time in a discrete event system does not proceed linearly but in irregular intervals [11].

Main discrete event simulation application areas are: material flow simulation, manufacturing system analysis, and information flow simulation. These applications can be decomposed into smaller, more precise tasks to examine, e.g., inventory, work in process, queues or transporting time.

2.3.2. Geometric simulation

Contrary to discrete event simulation, geometric simulation proceeds time-linearly, and therefore also is referred to as continuous simulation. *Geometric simulation systems* simulate the geometry of a part

Table 1
A selection of the benefits and the limitations with simulation

Benefits	Limitations
possible to try alternatives without heavy machine investment	hard to determine the level of detail for simulation model [6]
provides a solid ground for wiser decisions	hard to find the right objective/unrealistic goals
no disruption of ongoing on-line operation	a model is only an abstract simplified representation of reality [7]
experiments with time (lead/mean/cycle) possible	scarcity of knowledge about simulation modelling
problems can be detected before they reach the shop-floor	sometimes hard to analyse the results [4]
new situations can be explored	time-consuming
good knowledge of the system can be gained	expensive software and hardware needed

of, or the whole manufacturing system, usually in three dimensions. In other words, the production engineer builds a virtual manufacturing system with its equipment and control logic, for simulation of manufacturing functions. This type of simulation is also called *virtual manufacturing*.

Many geometric simulators were explicitly developed for simulation and off-line programming of robots, and they are grouped under the term Computer-Aided Robotics (CAR). CAR systems have gradually evolved and now they can handle more complex simulation of the whole manufacturing system.

Main geometric simulation application areas are: 3-D visualisation, geometric manufacturing system simulation, off-line programming of robots and collision detection. These applications can be decomposed into smaller, more precise tasks to examine, e.g., cycle-times, speed, layout, or robot motions.

2.4. Integration in simulation

In this section, three important issues for manufacturing simulation are discussed: (i) the importance of simulating and analysing also Shop-floor Control Systems, (ii) the advantage of integrating discrete-event and geometric simulation analysis of the manufacturing facilities, and (iii) the advantage of having a good interface between the virtual and the real shop-floor.

The close relationship between a manufacturing system and its shop-floor control system is evident: the functions and behaviour of the control system strongly affect the flow of parts and material. Therefore, analysing the parts flow without fully considering the control system can result in wrong conclusions. Concurrent simulation of the information flow in the shop-floor control system and the physical system's material flow, makes it possible to evaluate not only the chosen layout, resources, etc., but also the control system and its behaviour.

Traditionally, discrete-event simulation has been used mainly for analysing the flow of parts and material on the shop-floor. However, many discrete-event simulators can be used also *for information flow simulation and analysis*, making it possible to model and simulate the information flow in shop-floor control systems. The simulated control systems can control (i) a model of the manufacturing facility in either a discrete-event or a geometric simulator, (ii) the real-world facility, (iii) or a combination of simulated and real worlds. In this way, the accuracy of the simulation analysis and the visibility of the simulation are increased.

Some software vendors offer interfaces that make it possible to directly integrate discrete-event and geometric simulators. When combining both types of simulators, the control logic for the specific equipment can be simulated in the geometric simulator, while supervisory controllers are simulated in the discrete-event simulator. The integration between the two types of simulators opens up a new perspective for simulating all aspects of a virtual factory. Improved integration of the two types of analysis has the potential of increasing quality since simulation input data can become more accurate.

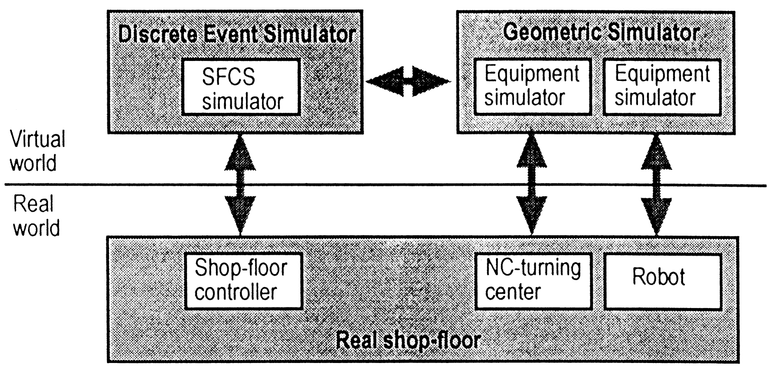

Fig. 2. Links between discrete-event and geometric simulators and manufacturing equipment and shop-floor control system (SFCS) on the real shop-floor.

Another important issue for simulation and shop-floor control is the *link to the real shop-floor*. The virtual factory model need not serve only as a stand-alone simulator; it can also be an integral part of the factory system [14]. This means that the simulator can be seen as an integrated part or a mirror image of the real shop-floor. All simulated control logic could be transferred to the real shop-floor through integration interfaces, and real-world manufacturing data can be used in simulation analysis to improve quality. The links between discrete event simulator, geometric simulator, and real shop-floor are displayed in Fig. 2.

3. Simulation software tools

The development of simulation software tools is rapid at this time, due to for example increased interest in simulation by manufacturing companies. An overview of simulation tools for Computer-Aided Production Engineering can therefore only show the software status as it is at the present time, and will soon become out of date. Still, there is a need to get an overview, i.e., an overall picture of what simulation in manufacturing can offer at the moment, and to identify where research and development efforts are needed most.

Other overviews of *simulation tools for manufacturing* have been carried out by Nwoke and Nelson [12] and Kosturiak and Gregor [13].

One of the hardest things in this type of research is to decide what software should be included in the overview. In this paper, several types of simulation tools are excluded since they do not correspond to the objectives of the paper (see Section 1). Although the research aims at including all major commercial simulation tools for CAPE, a reservation must be made; the list is not necessarily 100% complete.

Table 2
Discrete event simulation software tools and their vendors

DES Software	Company
Arena	Systems Modelling
AutoMod	AutoSimulations
DE3	BYG Systems
Extend	Imagine That
Factor/Aim	Pritsker
Micro Saint	Micro Analysis and Design
ProModel	Production Modelling of Utah
Quest	Deneb Robotics
Simple++	Aesop
Taylor II	F&H Simulations
Witness	Lanner Group

Table 3
Geometric simulation software tools and their vendors

GS Software	Company
CimStation	SILMA
GRASP	BYG Systems
IGrip	Deneb Robotics
Robcad	Tecnomatix Technologies
Workspace 4	Robot Simulations

The simulation software tools included in the overview are displayed in Tables 2 and 3.

3.1. Overview features

This section shows the features used to characterise the different simulation tools. It aims at showing the whole picture of what this type of software can offer. The actual overview results are displayed in Tables 4a–b and 5.

Since discrete event and geometric simulation differ fundamentally in some aspects, their features are displayed in two separate tables. However, there are some overview features that are common to both types of simulation tools that should be considered before investing in simulation software. These common features are:

- *Manufacturing application* indicating the possible application areas (in manufacturing) of the software, e.g., material handling or 3-D visualisation.
- *Hardware platform* showing the hardware platforms that are supported by the software, e.g., Workstation, PC or Macintosh
- *Software platform* showing the software platforms that are supported by the software, e.g., UNIX or Windows
- *User interface* points out what type of environment that the user faces, e.g., menu bars, dialog boxes, 2-D or 3-D animation.
- *Integration interface* showing what kind of interfaces the software offers for easy data transfer, e.g., simple data (ASCII), database data or CAD-file transfer.

Table 4
Overview of discrete event simulation software tools[a]

(A)	Arena	AutoMod	DE3	Extend	Factor/Aim	Micro Saint
Extra modules	MP$im: manufacturing Preactor: finite capacity scheduling BPSimulator: BPR tool	Kinematics: Auto View: animations AutoStat: enhanced statistics IGES/Sim: CAD file transfer	Conveyor design module	Extend + Manufacturing Extend + BPR	Factor PM: order, monitoring and tracking Factor SMM: schedule management	ActionView: 2-D animation tool
Manufacturing application	Material flow analysis Information flow analysis Capacity analysis	Material flow analysis Manufacturing system analysis 3-D visualisation	Material flow analysis Manufacturing system analysis 3-D visualisation	Material flow analysis Information flow analysis	Material flow analysis Manufacturing system analysis	Material flow analysis Manufacturing system analysis
Hardware platform	PC	HP, SGI, Sun, PC	HP, SGI, Sun, PC	PC	PC	SGI, Sun, Macintosh, PC
Software platform	Windows	Unix, Windows	Unix, Windows	Windows	Windows	Unix, MacOS, Windows, OS/2
User interface	Menu bars, icon panels, dialog boxes 2-D animation	Menu bars, icon panels, dialog boxes, 3-D animation	Menu bars, icon panels, dialog boxes, 3-D animation	Menu bars, icon panels, dialog boxes 2-D animation	Menu bars, icon panels, dialog boxes 2-D animation	Menu bars, icon panels, dialog boxes 2-D animation
Integration interface	ODBC, OLE Visual Basic DXF import	IGES Cimtechnologies Corp. products (Factory-FLOW, PLAN and CAD)	Data file transfer IGES, STEP	General languages, e.g., C, Fortran	Data file transfer	Data file transfer

Programming language	SIMAN: simulation language Cinema: animation language	English like scripting language: e.g., if-then-else logic, while loops	Simulation language: i.e., repeat, goto, if and wait commands	ModL: script simulation language	Process flow language	The ‘parser’: converts mathematical and/or logical expressions into computer code
Shop-floor integration	On-line communications with external applications like SFC and PLC systems	AutoSched: finite capacity planning and scheduling, integrating MRP and shop-floor control	Through GRASP (Table 5)		Factor applications: capacity, logistics and production scheduling on-line status of the shop-floor	
Reporting possibilities	Automatic standard output statistics Input analyzer: data fitting Output analyzer: enhanced statistics	Automatic standard output statistics Gantt charts AutoStat: design of experiments, enhanced statistics	Automatic standard output statistics User definable formats	Automatic standard output statistics	Automatic standard output statistics	Automatic standard output statistics
Link to GS software		Limited GS possibilities included, due to 3-D environment	GRASP (Table 5) Simulates continuous motions			
Other features	AST—Application Solution Templates Visual Basic for applications On-line help	3-D graphics editor Templates for, e.g., conveyor and AGVs Human operators can be modelled On-line help	3-D solid modelling tool Human operators can be modelled Recording of animations	Possible to run continuous simulations for DES input values	Cost modelling and simulation (ABC) On-line help	Task network modelling: activity model with sequence
Vendor contact (phone, homepage)	+1-412-741-3727 www.sm.com	+1-801-298-1398 www.autosim.com	+44-602-252-221 www.bygsys.co.uk	+1-408-365-0305 www.imaginethatinc.com	+1-800-428-7636 www.wintek.com/pcorp	+1-303-442-6947 www.madboulder.com

Table 4 (continued)

(B)	ProModel	Quest	Simple + +	Taylor II	Witness
Extra modules	Shifts: work and break schedules SimRunner: optimisation software Stat::Fit:	Deneb / Ergo: human modelling and simulation	Simple + + _C Simple + + _DDE Simple + + _GA Simple + + _gantt Simple + + _IPC Simple + + _Mailbox Simple + + _SQL	Advanced statistics Animator: shaded 3-D animation module Runtime development kit	XA: enhanced statistics
Manufacturing application	Material flow analysis Manufacturing system analysis	Material flow analysis Manufacturing system analysis 3-D visualisation	Material flow analysis Manufacturing system analysis Information flow analysis	Material flow analysis Manufacturing system analysis	Material flow analysis Manufacturing system analysis
Hardware platform	PC	DEC, HP, IBM, Intergraph, SGI, Sun, PC	DEC, HP, IBM, SGI, Sun, PC	PC	DEC, HP, IBM, VAX, Sun, PC
Software platform	Windows	Unix, Windows	Unix, Windows	Windows	Unix, Windows, OS / 2
User interface	Menu bars, icon panels, dialog boxes 2-D animation, 3-D perspective animation	Menu bars, icon panels, dialog boxes, 3-D animation	Menu bars, icon panels, dialog boxes 2-D animation	Menu bars, icon panels, dialog boxes 2-D animation, shaded 3-D animation	Menu bars, icon panels, dialog boxes 2-D animation
Integration interface	OLE capability	CGS, DXF, IGES, STEP and VDA Catia, Pro / Engineer, Unigraphics	Simple + + _C: C interface Simple + + _SQL: SQL database interface Simple + + _DDE: DDE interface Simple + + _Mailbox and Simple + + _IPC: inter process integration	Data file transfer C, Basic and Pascal interface DDE interface HPGL import	OLE capability ProSim: process mapping tool from Knowledge Based Ststems Inc. Possible to execute C programs

Programming language	Script simulation language: including, e.g., if-then-else logic, boolean expressions	SCL—Simulation Control Language: simulation language	SimTALK: simulation language	TLI—Taylor Language Interface: macro language	Action Language: BASIC-like simulation language
Shop-floor integration		BCL—Batch Control Language: send and receive signals from, e.g., PLCs, robots Tehdasmallit Oy products (PLCLink and SysLink)	DDE or RPC connections to shop-floor systems (operating system dependent—Unix or Windows NT)		
Reporting possibilities	Automatic standard output statistics Stat::Fit: distribution fitting, e.g., parameter estimates, graphical analysis	Automatic standard output statistics Enhanced statistics 2-D draw world: generation of CAD drawings	Automatic standard output statistics Simple++_gantt: Gantt charts	Automatic standard output statistics Advanced statistics, input/output analyzer: enhanced statistics, user defined reports	Automatic standard output statistics XA: enhanced statistics Design of experiments
Link to GS software		Igrip (Table 5) Simulates continuous motions	Limited connection to Robcad (Table 5) through ROSI and Simple++ Mailbox		
Other features	RTI—the runtime interface: design of experiments Shifts: work and break schedules SimRunner: optimisation software	Cost modelling and simulation (ABC) Recording of animations	Application object templates: i.e., shop-floor structure conveyors AGVs and staff Simple++_GA: optimisation software	Runtime development kit: allowing creation of customised application	
Vendor contact (phone, homepage)	+1-801-223-4600 www.promodel.com	+1-810-377-6900 www.deneb.com	+49-711-138-900 www.aesop.de	+1-801-224-6914 www.taylorii.com	+1-216-519-1200 www.lanner.com

[a] Vendor Product Information—for more information about specific software, please contact the vendor. Phone number and homepage address can also be found in Table 5.

Table 5
Overview of geometric simulation software tools[a]

	CimStation	GRASP	IGrip	Robcad	Workspace 4
Specific application modules	ArcWeld SpotWeld Paint Polishing	Arc welding Spraying pattern design Robotic palletising	UltraArc UltraSpot UltraPaint UltraFinishing Deneb/Ergo	Spot Arc Paint Gun Fixtures OLP Drill Laser Man DYNAMO	Robotrak for calibration
Manufacturing application	3-D visualisation Geometric manufacturing system simulation OLP Collision detection	3-D visualisation Geometric manufacturing system simulation OLP Collision detection	3-D visualisation Geometric manufacturing system simulation OLP Collision detection	3-D visualisation Geometric manufacturing system simulation OLP Collision detection	3-D visualisation Geometric manufacturing system simulation OLP Collision detection Spot welding Arc welding Paint spraying Deburring Polishing
Hardware platform	HP, IBM, SGI, Sun	HP, SGI, Sun, PC	DEC, HP, IBM, Intergraph, SGI, Sun, PC	HP, IBM, SGI, Sun	PC
Software platform	Unix	Unix, Windows	Unix, Windows	Unix	Windows
User interface	Menu bars, icon panels, dialog boxes—3-D animation	Menu bars, icon panels, dialog boxes—3-D animation	Menu bars, icon panels, dialog boxes—3-D animation	Menu bars, icon panels, dialog boxes—3-D animation	Menu bars, icon panels dialog boxes—3-D animation
Integration interface	CADDS, Catia, Pro/ENGINEER, Unigraphics IGES, STEP	IGES, STEP IRL	AutoCAD Catia, Intergraph, Unigraphics DXF, IGES	AutoCAD, Catia, Unigraphics DXF, IGES, SET, STEP, VDAFS	DXF, IGES, STEP

	Other Silma products: (Soft Assembly, Soft Machines, CimStation Inspection, AdeptRapid)	DE3 (Table 4a)	Quest (Table 4b)	Simple++ (Table 4b)	
Programming language	SIL—LISP like language, compiles to C	GRASP simulation language: e.g., repeat, goto, if and wait commands	GSL—Graphical Simulation Language	TDL—Task Description Language	Uses the robot language directly (Karel 2 default simulation language)
Shop-floor integration	Direct downlowd of program to target robot	Direct downlowd of program to target robot	Direct downlowd of program to target robot	Direct download of program to target robot	Direct downlowd of program to target robot
Reporting possibilities	Output drawings 3-D visualisation recording VRML	3-D visualisation recording VRML	3-D visualisation recording VRML	3-D visualisation recording VRML	3-D visualisation recording VRML
Robot language support	AIM, Arla, Karel, Nachi, ROPS, Panasonic Rail VAL2	Arla, Carola, RCM3, RRL, VAL2	Acma, Arla, Cimpler, Cloos, Comau, Cybotech, GMF-RC/RG, Graco, IGM, Karel, MOT-ERC/MRC, MOT-ERC/MRC, Nanchi, Rapid, RJ-KAREL/TPE, Robtalk, ROPS, ROPS2, VAL2	Acma, Arla, BEHR, Cinci, CNC, IGM, GMFR/C, Karel, KPAS, Kawasaki, Modicon, Nanchi, NCPainter, RCM, S1, S7, Robtalk2, TR4000, VAL2, Vplus, VRS	Karel 2, Karel 3, Arla, TL-1, Rapid, Slim, AS, PDL2, AML2, Parl, Fara, ACL, TP, ValI/ValII, V/V+Inform 1 and 2 MMBasic
Other features	Calibration tool Robot library	Calibration tool Robot library	Calibration tool Robot library	Calibration tool Robot library	Calibration tool Robot library
Vendor contact (phone, homepage)	+1-408-432-1260 www.silma.com	+44-602-252-221 www.bygsys.co.uk	+1-810-377-6900 www.d eneb.com	+1-810-471-6140 www.tecnomatix.com	+44-191-272-3673 www.rosl.com

[a] Vendor Product Information. Phone number and homepage address can also be found in Table 4a,b.

- *Programming language* giving the name of the programming language used for, e.g., adding if-then-else logic to a simulation.
- *Shop-floor integration* indicating if the software has an interface to the real shop-floor, e.g., robot controller
- *Reporting possibilities* indicating if the software supports documentation of the simulations with, e.g., output statistics or recorded animation.
- *Other features* showing other specifically interesting features of the software.

Additional features for the overview of discrete event simulation tools are:

- *Extra modules* showing the extra available modules that add functionality to the software.
- *Link to geometric simulation software* indicating if there are links to geometric simulators.

Additional features for the overview of geometric simulation tools are:

- *Specific application modules* listing the extra application modules available.
- *Robot language support* listing the robot languages possible to compile and/or translate for direct download to robot controller.

4. Discussion

The following discussion summarises important insights gained from the results presented in Table 4a,b and Table 5, and deals with the trends that can be identified for the near future.

Manufacturing application: Application areas differ very little from the applications mentioned in Sections 2.3.1 and 2.3.2, which means that discrete event and geometric simulators are still used for different purposes. Yet, they tend to overlap in some areas, mainly for 3-D visualisation. Links between simulators are becoming more and more common for this purpose, as discrete event simulators use the 3-D animation of the geometric simulator.

Hardware platform: There is a strong trend towards PC-based simulation software, especially among the discrete event simulators, where some vendors concentrate only on PCs. Even heavy 3-D animation can be run on PCs nowadays with fairly good results. However, the heaviest 3-D animation still needs workstation capacity.

Software platform: The trend towards PC hardware directly led to the trend towards Windows-based software (Windows 3.11, Windows NT, Windows 95, Windows 97).

User interface: Tendencies towards 3-D animation for discrete event simulators can be identified. User-friendly interfaces with menu bars, icon panels, and dialog boxes are used by all simulators, but a lot more can be done in this area. The training periods are long, due to (too) many possible choices and functions within the software. There is a need for software that is easy and fast to learn. This can be achieved through more application-specific software.

Integration interface: Many discrete event simulators have interfaces to, e.g., databases, spreadsheets and/or external programming languages. Many geometric simulators have direct interfaces to commercial CAD software and possibilities to transfer standard files (STEP, IGES). There is a trend towards open systems which indicates more standardised interfaces on the whole, with special emphasis on Windows (DDE, OLE) and STEP.

Programming language: All simulation software uses some kind of simulation programming language, additional to the programming possibilities with, e.g., icon panels and menu bars. There is no standard simulation language, but most of them are based on traditional programming languages like BASIC, C, or Pascal.

Shop-floor integration: There are some links between discrete event simulators and the real shop-floor, like links to PLCs. The geometric simulators all have download possibilities for off-line programmed robot programs. If the connection to the shop-floor is going to develop, there is a need for more open systems, so that the software can communicate securely in a standardised way with different hardware and software systems.

Reporting possibilities: Discrete event simulators all have some kind of standard output of statistics presented, e.g., in tables, bar- or pie-charts. Some vendors offer enhanced statistics with, e.g., confidence intervals, warm-up statistics, or fitting of data to standard distributions. Geometric simulators usually include the possibility to record the simulation like a movie clip and to export VRML code. Internet can then be used when distributing the simulation results.

Extra modules: Many discrete event simulators have extra modules for, e.g., enhanced statistics or animation while some simulators include these features in the basic package. It is likely that specific application modules will be developed in the future, giving the customer the possibility to tailor the software to his exact needs. Today, these specific applications must be programmed by the customer himself via application templates.

Link to geometric simulation software: Some discrete event simulators have direct links to geometric simulators, which gives many advantages, e.g., to get the right input variables for cycle-times or to use the 3-D animation environment of the geometric simulator. The connection between discrete event and geometric simulators will be emphasised in the future—through standardised communication interfaces—also between software from different vendors.

Specific application modules: Most geometric simulators have specific application modules. This gives the advantage of tailored applications that are readily learnt compared to big ‘all in one’ packages. We will probably see more application modules in the future.

Robot language support: All geometric simulators support a number of robot languages that can be translated or compiled. Some vendors offer direct programming in the chosen robot language.

4.1. Research and development areas

Even though the development of simulation software tools has been rapid the last couple of years, there are still many things for researchers and developers to investigate and work on, some of these are the following.

- The scarcity of knowledge about Computer-Aided Production Engineering among a broad spectrum of employees working with manufacturing, needs to be addressed. The necessary competence can only be obtained through education.
- Many software tools are ‘over-engineered,’ resulting in long training periods and expensive software. There is a need for more application-oriented software easy to use also for people working close to the process.
- There is a need for a structured way of working with simulation software tools. A methodology would give support in this area, indicating how and when to use the software tools in the best possible way.
- The integration with other software systems is an important issue. This integration can only be reached through systems that are *open* for communication with other systems.
- The links from the simulation software tools to the real shop-floor need to be emphasised. A central question is how to control and adjust differences between the computer model and the equipment on the real shop-floor (calibration).
- Version handling becomes an important issue as models must be updated when something changes on the shop-floor. There might be a need for PDM-like systems for simulation models that can handle this problem.

5. Conclusions

Development of manufacturing systems often is supported by computerised tools, among which simulation tools are becoming increasingly important for the decision making. This paper has presented a comprehensive overview of commercial simulation software tools used in Computer-Aided Production Engineering. Furthermore, trends in manufacturing have been discussed, for instance open systems with integration interfaces to other software, simulator integration with the shop-floor, and the modularization of simulation software. Research and development areas have been identified and discussed, for example the need of education in CAPE technology, structured work using models, architectures and methodologies, and integratable software—between discrete event and geometric simulators as well as between simulators and the real shop-floor.

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