2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering Education for 130 Years
ASEE
Paper ID #39232

Development of a SimEvents Model for Printed Circuit Board (PCB) Assembly Processes

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Abstract

Industry 4.0 creates numerous opportunities while at the same time it imposes challenges to workforce development to take full advantage of emerging technologies and processes that are enabling new era of manufacturing. One of the key enabling technologies is Digital Twin, which is a foundation of smart and flexible manufacturing. Digital twin provides several capabilities to engineers: (a) what-if analysis during design process, (b) predictive health-based maintenance, and (c) process control and adaptive scheduling. This paper presents an approach to introduce modern modeling tools, such as MATLAB/SimEvents, in the undergraduate and graduate level manufacturing courses. It provides an example of student work which showcases student's creativity in application of tools to analyze printed circuit board (PCB) assembly process.

Introduction

Recent developments in computer technology, communications technology, data analytics, machine learning, artificial intelligence to name a few, have ushered a new age of advanced manufacturing known as Industry 4.0. One of the emerging concepts that is based on these technological advancements and have opened numerous opportunities for significant manufacturing process improvements is a Digital Twin [1, 2]. Digital twin is a digital representation of a physical system, commonly in a form of a mathematical model that represents dynamic behavior of a cyber-physical object. Digital twin provides several capabilities to engineers: (a) what-if analysis during design process, (b) predictive health-based maintenance, and (c) process control and adaptive scheduling. According to Grieves and Vickers "While the terminology has changed over time, the basic concept of the Digital Twin model has remained fairly stable from its inception in 2002. It is based on the idea that a digital informational construct about a physical system could be created as an entity on its own. This digital information would be a twin of the information that was embedded within the physical system itself and be linked with that physical system through the entire lifecycle of the system" [3].

Digital twin has evolved over time to the point that we realize three different variants: (a) digital model, (b) digital shadow, and (c) digital twin. Digital model is a traditional mathematical model which encompasses all necessary information describing the object/system. It commonly provides information on system geometry, along with bill of materials, and more recently started to include information on system behavior, e.g., kinematics and dynamics. Digital model is useful in designing the system and performing "what-if" analysis for the sake of system optimization, and prior to committing to production. Digital shadow is extension of digital model to application in system operation where the model is connected to the real physical system, receives data/information from the system and performs analysis of current performance and predicts future performance. This is very useful in health monitoring and predictive maintenance, where digital shadow can predict the remaining useful life of the system and recommend maintenance at the most appropriate time to reduce unnecessary interruption in the process. The information flow is a one-way, from the physical object to digital model. Digital twin provides extended capabilities to digital shadow by having a feedback connection to the physical object, allowing for process control and reconfigurability of flexible manufacturing system for optimal response to disturbances, process deviations, and possible system failures.

Digital twin concept has been embraced by various industries including manufacturing, agriculture, energy, etc. The global digital twin market size was valued at $11.12 billion in 2022 and is projected to have compound growth of 37.5% from 2023 to 2030 [4]. Hence, it is necessary to introduce this concept in undergraduate and graduate engineering programs so that graduates can be prepared for emerging technologies and needs of industry.

Digital twin concept has been introduced in the Mechanical and Aerospace Engineering MAE 785/885 "Advanced Manufacturing Technologies" course at Old Dominion University. The modern simulation tools, MATLAB with Simulink, Simscape, SimEvents, and Predictive Maintenance toolboxes are used to demonstrate and explore some of the aspects of digital twin. The process of integrating various aspects of digital twin in the existing courses takes significant time, and the initial step was focused on integrating the concept of digital shadow. For a term project, students were given a task to create a digital model of a realistic manufacturing process and perform process analysis and process optimization. The following example provides an insight into a typical term project and depth of the analysis performed by students.

Since the course is at the graduate level, the students were expected to be independent learners with appropriate, yet basic, background in modeling and simulation. The students were also expected to have some basic understanding of manufacturing processes and discrete event systems. Hence, the students were given MATLAB/Simulink and Simevents tutorials with number of examples and were asked to review them on their own and figure out how to apply these modern tools to simulate manufacturing operations. In rare cases instructor reviewed some of the topics related to simulation procedures and commands, but overall students were able to gain the command of the MATLAB and its toolboxes without any problems. Instructor did not spend any time teaching students basic programming skills or introducing MATLAB. The focus of the projects was to create arbitrary scenario for a manufacturing process of student's interest and see how the system behaves under different input conditions as well as system disturbances, and provide recommendations on how to address observed issues (e.g. bottle-necks in production, insufficient production level for desired output, impact of machine failure on process output etc.). Students created their own manufacturing scenarios and performed analysis and made appropriate recommendations. There were 24 students in the course, who were divided in teams of two students. At the end of the semester students submitted their projects and made presentations.

In the future, the course will be further modified to include projects related to both digital shadow and digital twin. The examples and term projects will address the issues of predictive maintenance, and flexible and reconfigurable manufacturing. The amount of theoretical and practical material that needs to be covered is significant and will require extended time to fully implement into the existing courses.

Student Projects – Example

Printed Circuit Boards (PCBs) are an integral part of any electronic device. They are basically the backbone that enables the components to communicate with each other. PCB assembly is defined as the process of mounting different electronic components to a PCB [5, 6]. In this work, a SimEvents model of PCB assembly process is designed and simulated based on MATLAB Discrete-Event System. The model consists of a machine for solder printing, two machines for pick and place components, a machine for reflow soldering and a machine for X-ray inspection. Each machine is represented as a subsystem. The number of PCBs departed from each process is plotted and discussed by adjusting the service time for the entity server of the pick and place machines. A general guideline for PCB manufacturing is detailed below.

A. Solder Paste Application

Once the Printed Circuit Board (PCB) is designed and fabricated, the assembly process begins with the application of solder paste on the contacts. Solder paste acts as the binding between the electronic components and the PCB. The application of solder paste changes based on the type of soldering, with modern PCBs using Surface Mount Technology (SMT). In SMT, solder paste application on a PCB is called Solder printing, which is a screen-printing process using a stencil. The solder paste is applied on top of the stencil using a squeegee, ensuring precise application only on the contacts. Factors such as squeegee speed and angle are crucial in achieving a proper application and eliminating imperfections. After the solder paste application, a manual or machine-based inspection called Solder Paste Inspection (SPI) follows to ensure the quality of the application.

B. Pick and Place

After the successful application of the solder paste, the different components can be fixed on to the contacts. This process is usually handled by a speed mounting machine. The pick and place machines use vacuum- or parallel-jaw- grippers to carefully pick and place the different components to the right places on the PCB. Before SMT was introduced, PCB components were attached to the board using through-hole technology, which involved connecting the leads of components through holes on the board.

C. Reflow or Wave Soldering

Reflow soldering is a subset of the surface mount process. At this stage of PCB fabrication, the PCB components are firmly attached to the contacts by melting the solder paste. When the solder paste melts and becomes liquid, it creates a bond between the component and the contacts. Reflow soldering can be done manually or with the help of ovens. One of the greatest risks involved in reflow soldering is overheating of the materials. This can cause damage to both PCBs and components, which can be prevented using temperature monitors and sensors.

There is another method of soldering called Wave soldering, which involves passing the PCB over a layer of molten solder, which attaches to the contact points containing the components. To prevent oxidation of the contacts and improve the chances of attaching solder to the contact points, the PCB is sprayed with a flux spray, preheated, and then carried over a wave of molten solder. This method is commonly used for through-hole design PCBs and can also work with surface-mount components, although it requires more planning in the case of double-sided designs. However, overheating during wave soldering is a significant risk that can damage both the PCB and components. Careful monitoring and temperature control are essential to ensure a successful outcome.

D. X-ray Inspection

After the reflow soldering process, the PCB with all of the components is sent for an X-ray inspection test. This test is used to gauge the quality of the solder joints. During the test, x-rays penetrate the silicon in IC packages and reflect off the metal joints, creating a grayscale image depicting metal in a darker hue. This image shows the precision of the solders and whether any defects exist, such as open solder joints, misaligned parts, or lifted pins beneath the IC packets. The X-ray image of the PCB is then compared to a reference image to identify any differences. If any misalignments are discovered, the component is sent back for repair.

Methods

A SimEvents model of PCB assembly process is designed and simulated based on MATLAB Discrete-Event System. The model consists of a machine for solder printing, two machines for pick and place components, a machine for reflow soldering and a machine for X-ray inspection test. Figure 1 shows overview of the SimEvents model where each machine is represented as a subsystem. The period of Entity Generator is set to 1, switching criterion of Entity Output Switch and Entity Input Switch are both set to round robin.

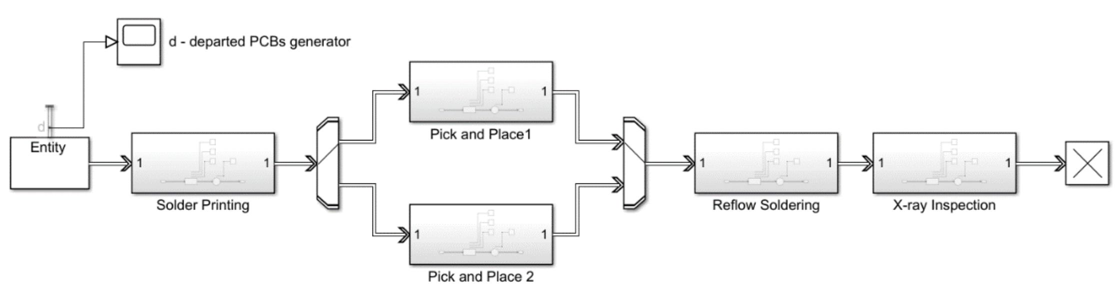

Figure 1. SimEvents model of PCB assembly process

Each subsystem consists of an Entity Queue and an Entity Server. Figure 2 shows the model of the solder print machine. Table 1 shows the summary of initial parameters of each Machine (subsystem). Generally, Solder Printing and Pick and Place electronical components in PCB assembly process take longer time than Reflow Soldering and X-Ray inspection.

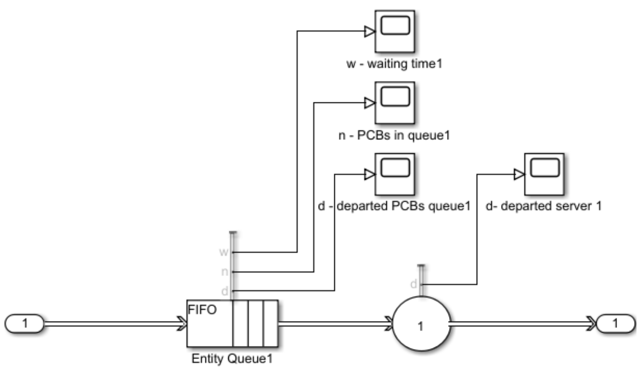

Figure 2. SimEvents model of the solder print machine

Machine	Queue Capacity	Server	
		Capacity	Service time
Solder Printing	10	1	1
Pick and Place 1	10	1	4
Pick and Place 2	10	1	4
Reflow Soldering	10	10	1
X-Ray Inspection	10	1	1

Table 1. Summary of Entity Servers

Experimental Results

The Stop Time of the simulation is set to 100. After running the simulation, the number of PCBs departed in each machine are observed. Number of departed PCBs from the Entity Generator are shown in Figure 3, and Figure 4 shows the Number of PCBs departed of Solder Printing process, as the PCB is generating, the number of PCB departed of the Solder Printing process increases.

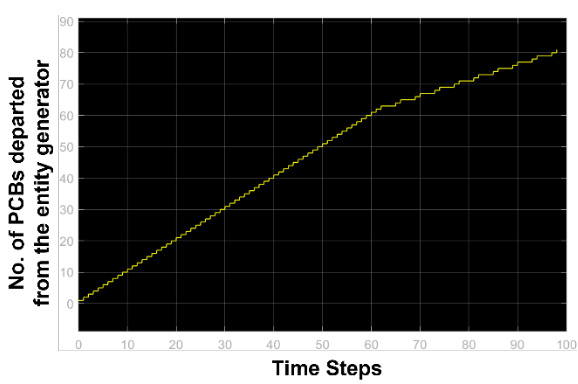

Figure 3. Number of departed PCBs from the Entity Generator

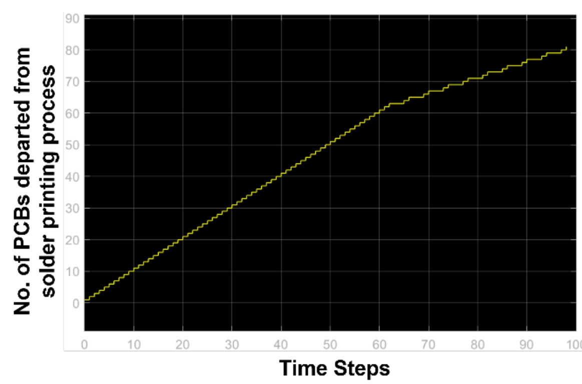

Figure 4. Number of PCBs departed from Solder Printing process

Figure 5 shows the Number of PCBs in queue of components Pick and Place process, two machines are used since this process usually take longer time than the others. The first PCB come after the Solder Printing process enters the first machine and second PCB enters the second machine for picking and place, that is why a 1 units of time delay is shown in the

Figure 5b, it takes 1 units of time to finish the Solder Printing. Figure 6 shows the Number of PCBs departed of Pick and Place process. Each PCB takes 4 units of time to process.

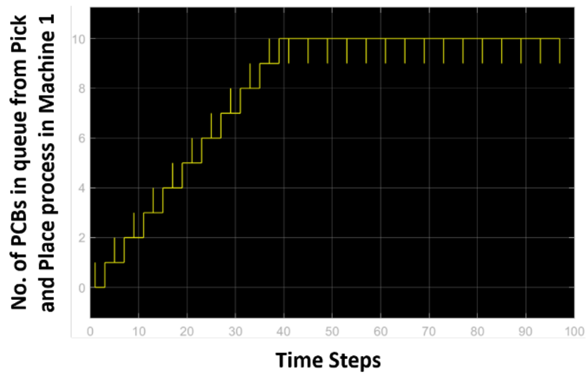

Figure 5.a. Number of PCBs in queue from Pick and Place process in Machine 1

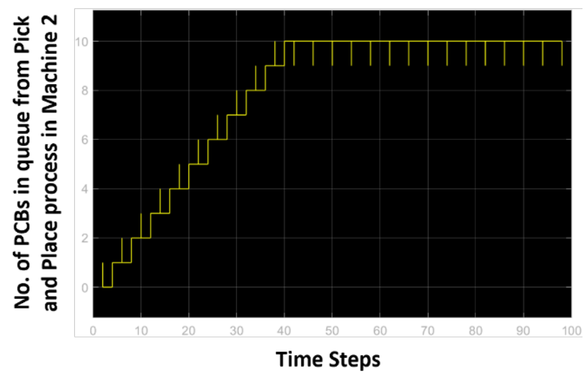

Figure 5.b. Number of PCBs in queue from Pick and Place process in Machine 2

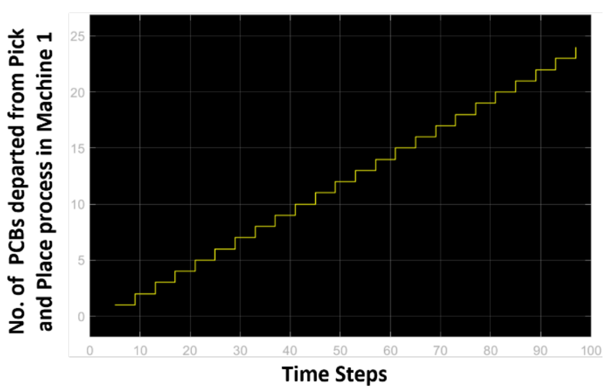

Figure 6.a. Number of PCBs departed from Pick and Place process in Machine 1, Service time of the Entity Server = 4 units of time

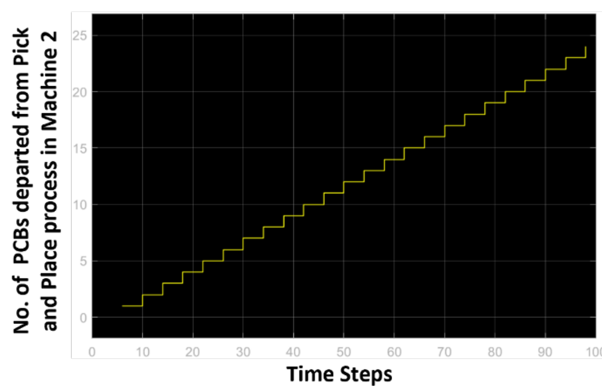

Figure 6.b. Number of PCBs departed from Pick and Place process in Machine 2, Service time of the Entity Server = 4 units of time

Figure 7 shows the number of PCBs departed of Reflow Soldering and X-ray inspection process. Although the cycle time for reflow soldering and X-ray inspection are 1 unit of time, each PCB still take more than 1 unit of time in both processes, which means the actual time is limited by the last step, to address this problem, Service time for the entity server of the Pick and Place machine is reduced from 4 to 2 units of time.

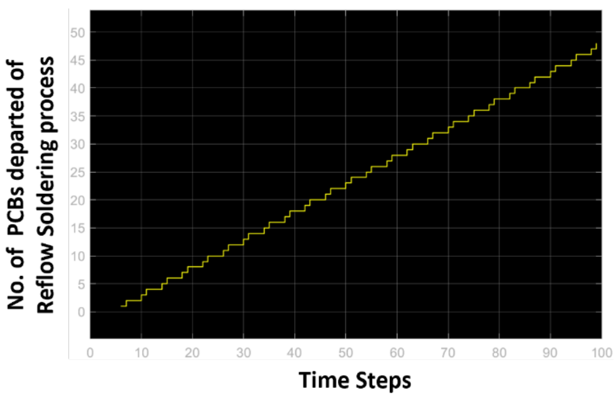

Figure 7.a. Reflow Soldering, number of PCBs departed, Service time for the entity server of the Pick and Place machine = 4 units of time

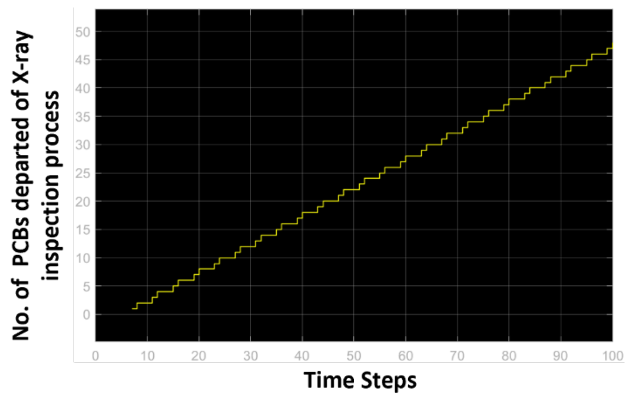

Figure 7.b. X-ray inspection, number of PCBs departed, Service time for the entity server of the Pick and Place machine = 4 units of time

Figure 8 shows the number of PCBs departed of Pick and Place process after Service time of the Entity Server is reduced to 2 units of time. Each PCB takes 2 units of time to process.

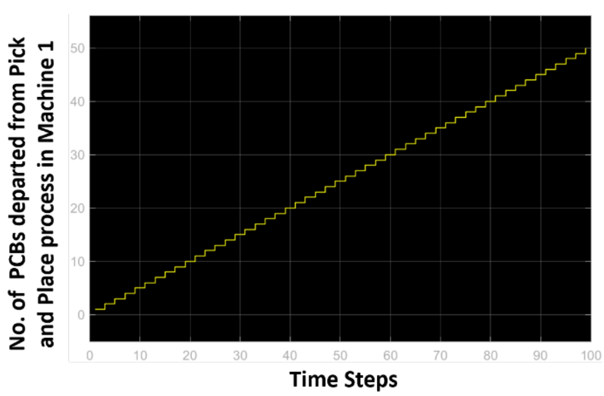

Figure 8.a. Number of PCBs departed from Pick and Place process in Machine 1, Service time of the Entity Server = 2 units of time

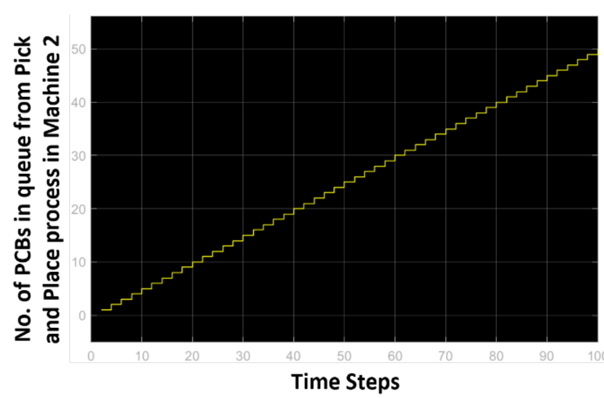

Figure 8.b. Number of PCBs departed from Pick and Place process in Machine 2, Service time of the Entity Server = 2 units of time

Figure 9 shows the number of PCBs departed of Reflow Soldering and X-ray inspection process after Service time for the entity server of the Pick and Place machine is 2 units of time, the cycle time for reflow soldering and X-ray inspection are exactly 1 unit of time, which is faster.

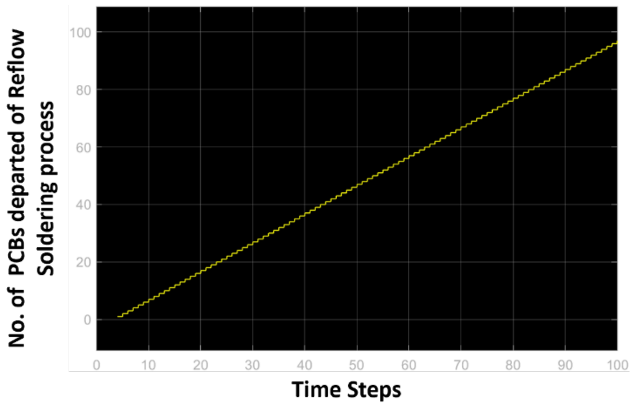

Figure 9.a. Reflow Soldering, Number of PCBs departed, Service time for the entity server of the Pick and Place machine = 2 units of time

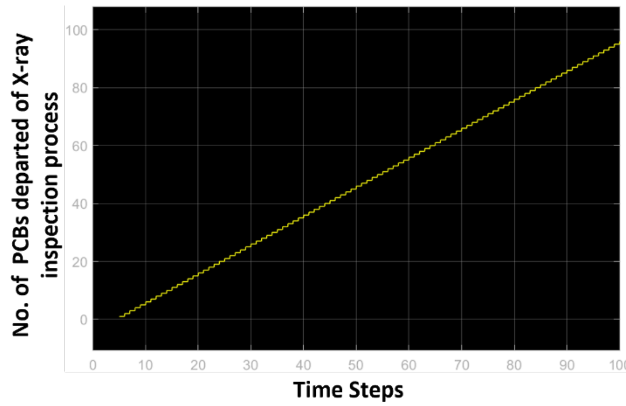

Figure 9.b. X-ray inspection, Number of PCBs departed, Service time for the entity server of the Pick and Place machine = 2 units of time

Discussion

A SimEvents model of PCB assembly process is designed and simulated based on MATLAB Discrete-Event System. The model consists of a machine for solder printing, two machines for pick and place components, a machine for reflow soldering and a machine for X-ray inspection, and each machine is represented as a subsystem. The slowest operation is the pick and place of electronic components. To address this problem, faster machines can be used to reduce the time needed for picking and placing. Alternatively, additional machines can be used for pick and place operations to improve the number of PCBs processed per unit of time.

Conclusions

The project received enthusiastic support from students. They appreciated the opportunity to learn modern tools that gave them the opportunity to address realistic scenarios and evaluate system performance under different operating conditions. The overall feeling was very positive and supportive of future application of modeling and simulation tools in the classroom.

In the future, the course will be modified to include aspects related to Digital Twin, where the system will have two models, one of the physical system (since we do not have access to real manufacturing system) and the other of the model based system. This will allow students the opportunity to control the system, predict time to failure, and failure causes. In essence, the students will have further opportunity to learn about the emerging technologies and tools that are applied in the real-world environment of Industry 4.0.

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