# Discrete Event Simulation in Electronics Manufacturing Operations

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**Abstract**

Every year, billions and billions of products are made and sold across the world. Each of these products, regardless of volume, are made in facilities that follow certain steps to assemble, test, and ship to customers. The steps that are taken to fulfill demand are an extremely interesting and valuable source of information. When modeled, simulated and analyzed, these steps can offer phenomenal insight on the overall process. This practice in the industry is called Discrete Event Simulation. Discrete Event Simulation, (namely DES) is the process of modeling a real-world phenomenon or system of operation as a sequence of discrete events. Discrete events in this context are described as instances that occur in a particular point in time with no change to the phenomenon or system between each event. Discrete Event Simulation is different than Continuous Event Simulation where the system is continuously changing due to a response to certain mathematical formulas and will not be covered in this paper. This paper will provide an overview of discrete event simulation in general, explain the different types of model taxonomy used in academia and industry, as well as discuss the importance and value of using these tools and practices in electronics manufacturing operations. Lastly, this paper will discuss challenges in adoption as well as a call to action for Discrete Event Simulation software providers and an outlook on where the industry is going from the perspective of Flex. In the context of this paper, “electronics manufacturing operations” refers to the assembly (both automated and manual), test (both automated and manual) and the shipping (both automated and manual) of electronic products.

**Introduction**

Before defining Discrete Event Simulation, this paper will first explore model taxonomy and how DES fits into the analysis of a system. Technically speaking, a system is defined as a collection of assets or entities (such as machines and people) that interact with each other to accomplish a goal. In this paper, the system will be defined as “electronic manufacturing operations” which refers to the assembly (both automated and manual), test (both automated and manual) and the shipping (both automated and manual) of electronic products. It is to be noted this definition of a system is specific to Flex, and that even though it may be similar to others it is being defined here for the sake of simplicity throughout this paper. In reference to electronic manufacturing operations, there are a multitude of ways that they can be studied. The figure below illustrates the ways that these systems can be analyzed.

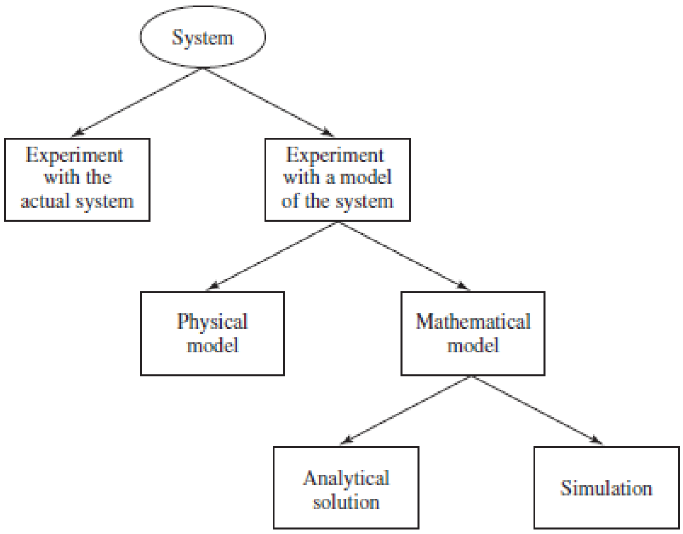



*Figure 1: Approaches to Analyze a System*

As seen above, a system can either be analyzed using actual experiments or experiments using a model of the system. One major advantage of DES is the ability to not have to perform an experiment on the actual system, a concept that will be covered in more detail later on. Since an experiment can be conducted on the model of the system, this allows for additional insight since it enables more data to be gathered and allows relationships in the system to be studied more in depth. For an experiment on the model of the system, there are 2 possibilities on how to do so; either using a physical model or a mathematical model. A physical model can be things like replicas, scaled versions of a system or even duplications of the system that are to be analyzed. The second way to study the system is to create and analyze a mathematical model of the system. The mathematical model approach consists representing the system in a series of logical and quantitative relationships that can be manipulated and modified to observe how a model reacts and thus, assume that it is how the real system would react given the same conditions. This is in most cases more reliable than a physical model since data is being captured and analyzed and also because relationships are being quantitatively (and also arguably qualitatively) represented. Once it is determined that a mathematical model will be used to study the system, there are 2 more choices that are available to proceed. The first, is that the mathematical model can be an analytical solution, this can be useful when the model is simple since basic mathematical or statistical calculations can help provide insights and can reach the results desired. However, in the majority of systems, as is the case for manufacturing operations, the system is extremely vast and highly complex, which in turn make the models complex, eliminating the possibility of working with an analytical solution. Due to this, a simulation is the best, complete and most accurate course of action. Once simulation is deemed to be the path forward, a number of dimensions need to be taken into consideration to determine what kind of simulation is the best suited for the application in mind. The first is whether the simulation will be a Static or a Dynamic simulation model. A Static simulation is where a system is represented in a either a point in time or where time does not affect the system. Conversely, a Dynamic simulation represents a system as it changes over time. Through years of simulation activities, it is believed that both Static and Dynamic simulations are useful in electronic manufacturing operations applications. Next, it must be determined if the model will be Deterministic or Stochastic. A Deterministic model does not deal with the concept of probability, meaning, that the system does not have any random variables and can be characterized through a calculated outcome or a given number of outcomes. A Stochastic model on the other hand, can use statistical algorithms to produce random outputs given the random variables and conditions of the model, as are most systems, such as electronic manufacturing operations. Due to the nature that this method is inherently random, it must be treated as such, one of the major limitations when used in a manufacturing operations environment. Lastly, the model needs to be classified as a continuous or discrete model as was mentioned briefly above. Since continuous models are understood to represent ever changing systems over the course of time, discrete models are used in electronic manufacturing operation systems since they represent the change of state in systems in defined and “discrete” steps. One key concept that is necessary to mention here is that not every model is inherently and totally continuous, and not every model is inherently and totally discrete. Depending on how a system is defined, even in electronic manufacturing operations, a model can be more of one than the other and therefore the approach that most simulation experts use is to determine which type of events are being evaluated more in the system and then take the necessary approach. Based on this context, it can be safely stated that due to the nature of manufacturing and its process, a manufacturing operation system is mostly best described by discrete, dynamic and stochastic model. Hence, discrete event simulation or DES is what will be used as the key technology and discipline in this study.

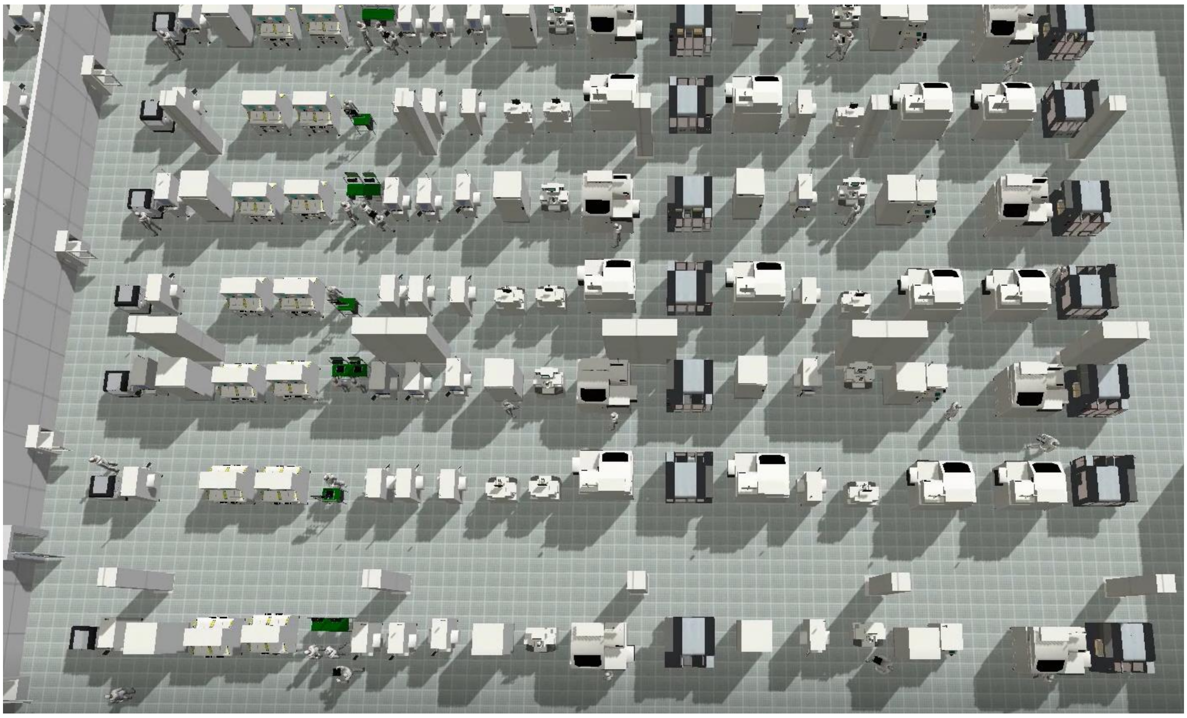


*Figure 2 - Example of a DES Model*

**Utilization of DES in Electronics Manufacturing Operation Systems**

Traditionally, electronic manufacturing operations systems consist of a number of methods that build electronic products. These include but certainly are not limited to Surface Mount Technology (SMT) lines, testing equipment (such as Flying Probe, ICT, FCT etc), dispensing equipment (such as conformal coating, underfill, potting, etc), manual assembly (such as hand soldering, odd form, PTH loading etc) as well as auxiliary operation systems such as material movement, supermarkets, Automated Guided Vehicles (AGVs) as well as pick, pack and ship operations in warehouses. These operations combined together are responsible for the creation of the electronic products that are used worldwide today. Since these operations are largely a combination of discrete events, it is highly valuable to use DES in these applications and DES has many benefits throughout the entire electronics manufacturing operations process. The best way to conceptualize and explain the usage of DES for this application is to think of a lifecycle that a product goes through to be manufactured, in the case of this paper, the products mostly referenced to will be electronic products. This lifecycle, which is used to help bring products from Feasibility to Phase Out, can be found below as reference.


*Figure 3: Flex Product Life Cycle*

Using the Product Life Cycle (PLC) as shown above, it is easier to conceptualize where and how DES can be used. Firstly, DES can be used in the Feasibility stage through the Concept stage as it pertains to electronics manufacturing. As a product is being designed and the manufacturing line for it is being set up, DES can be used in a variety of ways. Firstly, it can be used to visualize how the line will look like, this can be to validate the spacing that was allocated for it as well as to see how the line fits in with other assets that may already exist. Typically, at this stage, there is not much production relevant information available and therefore, a in depth industrial engineering analysis cannot be made although there might be enough information to visualize line basics. As the product moves further down the PLC, it enters into the Development and Production phases of its lifecycle. Here, there is a considerably larger amount of data and information that can be utilized to visualize, analyze and optimize the system. Since at this stage there is more operational data such as volumes, forecasts, and customer needs, DES can be used to create and validate the details of the manufacturing operations. Using the data provided, DES can help calculate how many stations, lines, headcount, and square feet will be needed. Industrial engineering metrics such as takt time, cycle time, yield and equipment efficiency can be modeled and validated to ensure that the correct resources are being utilized to achieve on time customer goals. At this stage of the PLC, it is common for products to either continue as they are, grow and expand, relocate and downsize and for all of these scenarios, DES can help verify and validate the way that the operations should proceed under the respective condition. A major advantage of object oriented based DES software is that it not only helps provide the mathematical analysis necessary to make these decisions but it also can provide a graphical representation which can be used help visualize not only the past and current state of operations but also the future state when needed. As the product enters into the final stages of its life in the Phase Out phase of the PLC, it is common for electronics manufacturing operations (as do other industries of course) to try and plan for the future of the space that was being used as well as plan for the future of how the product will end its life. In these cases, DES is very useful to plan how to start to either remove or reutilize stations, transfer headcount, plan for volume changes as well as start to introduce the next product onto a line while one product starts to taper off.

These applications of DES are pertaining to SMT related assembly processes. However, in other processes, such as testing, dispensing, material movement, supermarkets, Automated Guided Vehicles (AGVs) as well as pick, pack and ship operations in warehousing applications, DES has large amounts of potential as well. Traditionally, testing and dispensing are offline processes, and even if they are in line, they constitute their own "next event time advance" approach and the analysis done there can offer insights such as buffers, queuing logic, processing time optimization, station balancing, layout optimization and others. Line supplementation and support processes such as material movement, supermarkets, kitting, AGVs for replenishment and other types of similar activities can benefit greatly from DES. DES methodologies of queuing, arrival process studies, batch processing, and other similar approaches can be used to extensively study the components of these systems and analyze how to best optimize them for the operation to either reduce waste, shorten time or any type of improvement. Similar types of analyses can be used to study warehouse operations. As per standard warehouse operation, there are generally 8 main activities that take place in a warehouse; receiving, put away or storing, picking, packing, dispatching, returning, value adding, and transportation. For all of these activities, DES can be used for the visualization, analysis and optimization of each. It is important to mention at this point that even though all of these processes might seem to be differently operationally, mathematically, culturally and even logically, they can still be modeled using DES level logic since at their core, they are generally and commonly discrete events.

**Advantages and Disadvantages of Discrete Event Simulation in Electronics Manufacturing Operations**

As with any technology, there are advantages and disadvantages to using DES in systems modeling. Regarding advantages, the first and one of the major advantages is that real world phenomenon's with stochastic elements cannot always be mathematically modeled and evaluated and even more difficult is to represent this graphically or with objects. Using DES, these high complexity systems can be modeled and analyzed to help make business decisions and drive improvements in various ways to systems. It can be said with certainty as well, that in some cases and some applications, DES is the only way to study the system and make improvements on due to the fact the system is so large and complex that any other method would take years to first model, then statistically study and then to go and make the changes, (this is assuming of course that the real world system still exists and has stayed the same since the study had started). Secondly, perhaps the biggest of them all, is that since DES is a representation of a physical system, it allows the testing and experimentation of an existing or current system under various scenarios and provide insights based on them. This is a very powerful concept since in theory, a real-world model is being copied in a software created environment, (this will be covered more in detail in the "Future of Discrete Event Simulation in Electronics Manufacturing Operations" section). Thirdly, a very common use case and huge advantage of simulation is that it allows for the possibility of "what if" scenarios to be evaluated. This helps save a lot of time, resources and capital that would otherwise be used in trying to figure out which scenarios are the best for a specific situation. In an electronics manufacturing operations environment, where there is little to no time to make decisions on what is the option for a process, DES can save time and money. Fourth, due to the fact that the system is being represented by a model, it is easier to experiment and try various types of conditions without affecting the actual system or the process that is occurring. This is extremely valuable in high time constraint situations or when the actual line cannot be modified due to various reasons.

Naturally, as with anything, there are also disadvantages in utilizing this technology, especially in electronics manufacturing operations. Firstly, the model is often perceived to be a "unrealistic" representation of a real-world environment. This is due to many reasons, namely because it is impossible to take into account every single factor of a real world environment into a human generated software ecosystem. Not every possibility can be thought of and also natural events or random occurrences can not always be predicted. Secondly, the creation of a simulation takes time. Depending on the level of detail that is required for the simulation, projects can last a few hours up to several years depending on what is needed and what the desired output of the simulation is. The creation of a simulation requires dedication, proper training and experience to be able to draw reasonable and actionable conclusions from it which can sometimes take a while to gather the data, create the model and run the calculations. Lastly, it is imperative to understand that a stochastic simulation output is an estimate of a model's characteristic. Stochastic simulations are by nature, random, and therefore the outputs are estimations. Thus, it is absolutely critical that multiple runs of the model be run so that the entire system can be studied. The running of the model multiple times is especially an disadvantage in electronics manufacturing environments because there are already many processes that are inherently random (such as operator behavior, material movements by water spiders, customer demand, demand forecasting, supply chain planning and many more).

Overall, even though there are advantages and disadvantages in using simulation, this is the case for any type of advanced technology that is used anywhere, and all of these components need to be taken into account when using any technology in making technical and business decisions.

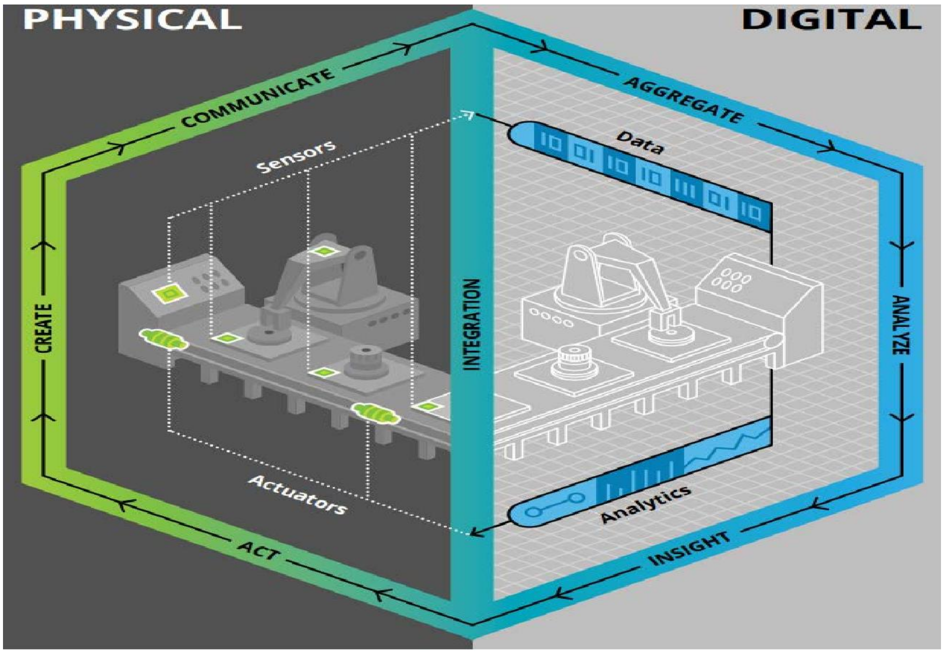
**Challenges of Discrete Event Simulation in Electronics Manufacturing Operations**

Discrete Event Simulation is already used heavily in industrial and manufacturing operations; however, it can be argued that it has not been used heavily in the electronics manufacturing operations industry for a multitude of reasons. Firstly, electronic manufacturing operation systems by nature are extremely dynamic and variable (or in DES terms, stochastic). This is due to the fact that most electronic manufacturing operations are done by contract manufacturers and are thus dependent on customer demand, customer forecast and technology trends of products which by nature have shorter product life cycles than other products in the world. These issues affect the systems greatly since even small changes in demand, supply, or technological innovation can largely affect how the system is operating. Secondly, in current times, electronics are being integrated into more products and devices in everyday items that are used by a majority of people, even though this is great news for electronics manufacturing companies, it creates the issue of balancing diverse supply chains, sourcing and stocking various raw and Work in Progress (WIP) material as well as planning and creating manufacturing lines for these types of products. The reason that this creates an issue is because since these types of products are very diverse and require different types of manufacturing lines and manufacturing processes, they create complicated working systems in a given facility. For example, a building might have several lines making a server for a telecom with a few lines making a consumer product in the area next to it. Simulating one of those product areas is easy since there is a method to what is happening for that certain product, however, when a simulation is needed for the entire area for reasons such as optimization or balancing, this can create considerable amount of issues since multiple combinations of logic are needed to accurately represent what is going on in the system, which, arguably, is two different systems being treated and simulated as one. Lastly, even though the majority of electronic manufacturing operations are represented by the idea that they are fabricating and assembling Printed Circuit Boards (PCBs), the manufacturing operations that take place after the board has been made, commonly referred to as Final Assembly, Test and Packout or FATP, are vastly diverse and these can create very unpredictable situations for a Discrete Event Simulation to properly capture.

**Future of Discrete Event Simulation in Electronics Manufacturing Operations**

The advent of various industry changing initiatives has put a spotlight on simulation in general and is creating a revival in the art and science of simulation itself. Industry driving trends such as connectivity, 5G, Internet of Things and most of all Industry 4.0 have generated more attention when it comes to technologies that enable greater insight into real world phenomenon. Simulation, which has been around for decades is undergoing a transformational shift, from becoming a tool that is used for optimization to become a tool that can be used for more predictive applications. Based on this as well as other industry driving trends as listed above a bright future can be seen for simulation in general, especially DES. Namely, it can be argued that simulation will become the digital blueprint for all manufacturing processes and become the backbone for all operations. The detailed justification for this belief is as follows. Today, factory floors have a layout which show the equipment that is present on the line. These layouts are made to scale and make sure that any type of production planning that is taking place is within the proper requirements for space in any given area. Additionally, production teams have documents that list the equipment that will be placed on the floor according to the layout. The documents that the teams have also list the capabilities of the machines both for the output as well as the overall functionalities of the equipment. Planning teams and industrial engineering teams have documents and files that have used both of these items, equipment lists and layouts to determine the headcount of people, as well as the rates and other industrial engineering metrics required for the lines to perform at to meet the required output. Today, all this information is stored on various documents, files, presentations on different computers with different people. Pertaining specifically to an electronics manufacturing operations system, much of the available data and information is not utilized due to it being deemed "unnecessary" or "irrelevant". At this stage, if a DES is implemented, it uses all the data that the teams had deemed to be important and the DES model starts to use this data to build the model. Recall from the outline of the model taxonomy, that a DES is a mathematical model and depending on the software, can represent the process through a graphics-based interface. This graphics-based interface is based on object-oriented programming and therefore, has 3 dimensional models of the equipment that is listed in the equipment list. These are represented as a visual model in the DES software. This might seem like a straightforward inclusion and capability; however, it is far more revolutionary than it might be perceived as. Due to the fact that a DES is a mathematical model of a system, and now this mathematical model is being represented by a 3-dimensional model, this allows engineers to start to mimic the activities of the machines in the software environment. If a physical machine that is on the line, based on the layout and the supporting documents and information listed above, and a 3 dimensional model of it is in the DES software environment, then technically speaking, there are 2 of the same object, one that is physical, and one that is digital. Traditionally, only the basic operative capability of the machine was used for standard industrial engineering calculations that were used to set up manufacturing lines. However, now, since there is a digital model of the same machine in the software environment, then, the remaining features and capabilities of the machines can start to be modeled as well. The greater detail that is provided by the 3-dimensional model, the more detail that can be included as per the capabilities of the real-world machine. Finally, if the machine that is in the real world is being modeled in the software and replicated as such, then additional electronic components can be added to the physical machine and the data can be streamed to the software which will then enable the 3-dimensional machine in the software environment to reflect this. If this happens continuously in a closed loop fashion, then we have what is commonly referred to in the industry as a Digital Twin. Since every machine is now doing this and the data that is being gathered and reflected is being involved more upstream in the manufacturing process and then is being utilized more downstream in the manufacturing process using the DES as a reference model, then there logically a "thread" that starts upstream and ends downstream connecting all of the processes with each other all the way through. This creates what is commonly referred to in the industry as a Digital Thread. Greater functionality can be added to the Digital Twin and the Digital Thread by incorporating sensors, actuators, PLCs, edge computer and other data gathering or data aggregating devices in the physical world and integrating MES systems, ERP systems, middleware, and cloud computing in the software world in the DES model that create tighter and more integrated processes throughout the entire manufacturing process which can provide greater insight in making business decisions. It is strongly believed that DES is the foundational software and logic that will be used as the groundwork for these types of integrations and technology driving operations. Further in the future, it is expected that DES will perhaps not be interfaced with as much since it will become more as an underlying engine that is being used across the entire ecosystem as opposed to being used in portions of the manufacturing process.

Overall, Discrete Event Simulation is believed to be used heavily in the future as more connected systems become prevalent, driven largely by macroeconomic shifts in manufacturing and industrialization (such as Industry 4.0). Even though DES and simulation in general has been around for decades, it has remained largely stagnant in terms of software capability with respect to added functionality in connectivity across various platforms (both hardware and software), data analytics and business intelligence. This lack of evolution of the product will be very detrimental to the growth and prevalence of this technology if software providers of DES do not realize it. Hence, this paper would like to also be represented as a "call to action" for DES software companies that they should now focus on this next generation of industrialization. The companies have done excellent work in incorporating mathematical prowess and statistical analysis to represent real world systems that can be used to visualize, analyze and optimize real world systems. However, it is imperative that these companies now focus on how to connect these tools across various platforms and devices in a Digital Thread to help create a powerful, useful, accurate and high-quality Digital Twin. It is believed that if DES companies will come forward and start to develop these types of functionalities and capabilities, they will be able to not only increase their market and enjoy the benefits of a growing business but they will be influence how the industry starts to utilize DES and drive market trends and uses even further in the future.



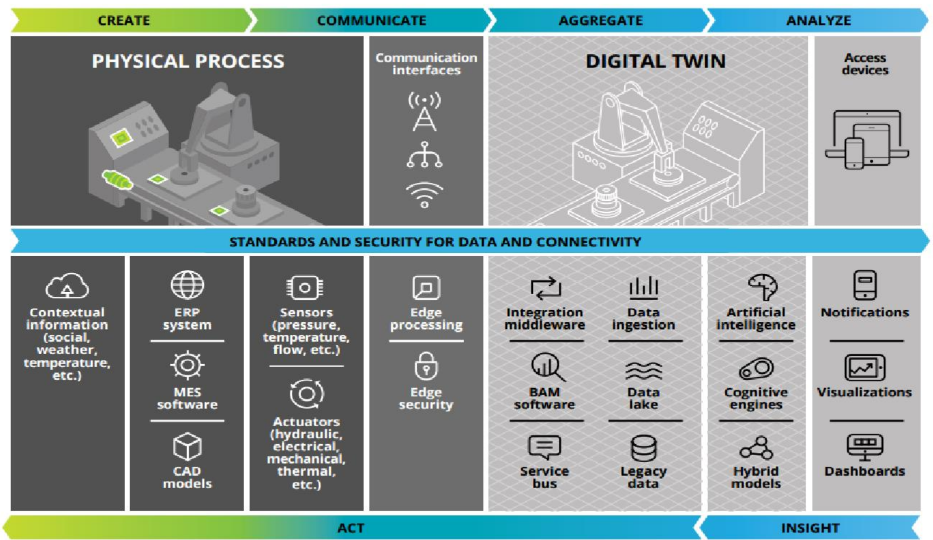



*Figure 4 - Digital Twin Concept*
Cartoon from article by Aaron Parrott and Lane Warshaw, Deloitte [82]

## Conclusion

Overall, as illustrated through this paper, Discrete Event Simulation is a very insightful technology, especially in the area of manufacturing operations systems and when utilized properly in systems such as electronic manufacturing operations systems, it can offer much needed information and data for driving effective and accurate business decisions. Of course, as with any aid tool, there are disadvantages and the outputs should be used as reference points and estimations but even such, a reasonable understanding can be drawn from these advanced tools. Due to the powerful algorithms and mathematical models that have evolved through the decades of the tools in the industry, as well as the growth and advent of industry revolutionizing initiatives such as the Internet of Things and Industry 4.0, a bright future is seen for simulation in general and especially Discrete Event Simulation. Concepts such as the Digital Thread and the Digital Twin will further drive simulation development in the industry and will help increase its adoption worldwide as well as give more reason for the tools to develop further and expand. Simulation has a bright future and it is exciting to think about what will happen in the coming decade with this fascinating technology and technique.