Chapter 2

Advantages of Learning Factories for Production Planning Based on Shop Floor Simulation: A Step towards Smart Factories in Industry 4.0

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Additional information is available at the end of the chapter

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Abstract

In future industry, defined as Industry 4.0, production planning and control strategies will be executed by human beings backed by computational tools for decision making; One of these tools is shop floor simulation, and a natural scenario to learn about how to use it for productive processes design and control are the Learning Factories. In this chapter, shop floor simulation is identified as a tool for planning and controlling production, also a state of the art about its implementation is exposed in academic and industrial environments. In addition, the trends in the construction of the Learning Factories are shown, and some aspects about how they can be used for shop floor simulation. This work also proposes the realization of a digital model in EAFIT University Learning Factory as a first step towards digital learning factory.

Keywords: digital learning factory, shop floor simulation, plant planning and controlling, discrete event simulation, Industry 4.0

1. Introduction: Learning Factories as simulated environments and innovation transfer actors

When a production system is being designed, builded or even working, there are several behaviors that cannot be described by exact mathematical equations (analytical models); for this reason, plant designers commonly use Virtual Design (VD), Shop Floor Simulation (SFS), heuristics or metaheuristic methods to predict possible critical situations once system is perturbed by use of supply chain, machinery, workstations cells, buffering and response time, equipment capabilities, etc. Some heuristic approaches are, for example, CRAFT algorithm used by Prasad et al. to optimize plant layout cost by machinery replacement [1] and Black Hole Algorithm used by Veres et al. to find optimal supply chains structure [2], which provide possible solutions in complex systems. However, SFS also allows to evaluate several system responses and to determinate optimal working conditions [3].

Simulation refers to Discrete Event Simulation (DES) which describe a model performance. According to Shanon [4], simulation is to design a real system model and carry out some experiences to learn its behavior and to evaluate strategies to understand how it works; it means that, in order to learn about system behavior, it is necessary an environment characterized by a high degree of fidelity regarding real system. That characteristic is typical of action-oriented learning methodologies such as role play [5], virtual reality [6], simulation [7] and Learning Factories (LF). Additionally, simulation has recently become a best valued teaching strategy by students [8], and LF are effective simulated environment tools for skills development through experiential learning [9]; its safe environments allow to face real industrial challenges with minimal abstractions [10] to replay to real situations in different knowledge fields during training process.

On the other hand, companies call for latest technical and technological knowledge and LF offer high potential for innovation transfer and application-oriented innovation platform of product and production processes research, and subsequent transmission of these innovations [11].

This article aims to provide a general state of the art of SFS based production planning in LF, seeks to define medium term research needs and proposes a research project to develop the EAFIT University LF digital model. It will be the starting point in the way to convert this LF in a digital Smart Factory towards Industry 4.0.

2. Shop floor simulation based production planning and control in Industry 4.0

SFS is commonly used to get information about production systems and is based on discrete events information related to resources flow and availability in the plant. In this context, a resource is everything needed for production (supplies and raw materials) and plant are the facilities used to transform those resources into a finished product (or service). Production system also involves other company areas not involved directly in product transformation but without whose existence production process would be much more complex and inefficient, for example: supply warehouse, packing, shipping, maintenance, etc. Interactions between all these areas are interesting for decision making and SFS lets to evaluate production capacity, inventory control, logistics, etc.

Currently, SFS role in Industry 4.0 context includes "real time" production programming and control. Some authors have suggested that using production system latest information and making simulations to predict events in the future it is possible to improve system performance by dynamically adjusting programming policies and control strategies [12, 13], it places SFS as an essential element in one of the four Industry 4.0 components, namely "smart factories" [14].

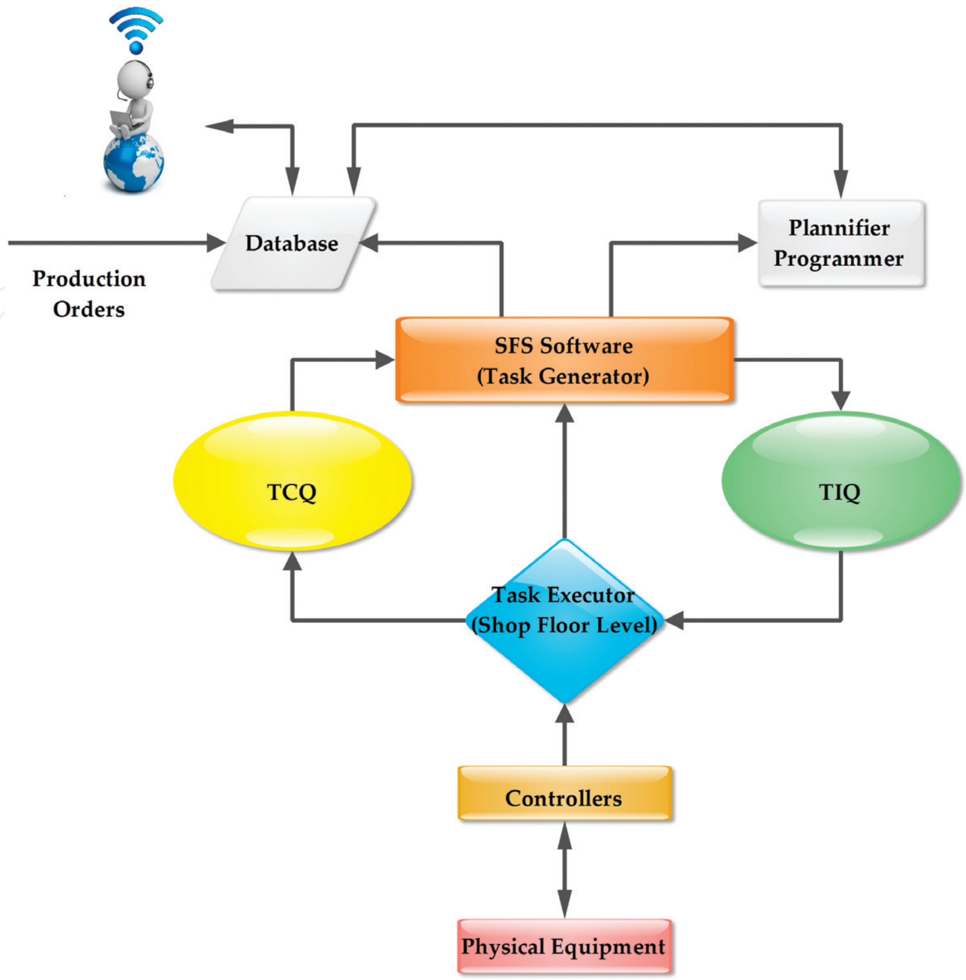

Figure 1. SFS based production control architecture in Industry 4.0. ([16] p. 382, 2005).

Figure 1 shows an example of SFS based production control architecture [15]. There is a task generation software used to develop simulation model which obtain production master programs (for example parts orders) and process plans from a database. The database keeps track part orders and quantity. Simulation control manufacturing system sends and receives messages and uses communication links to task executor; it performs execution functions at floor level and monitor part status in the system. Executor receives instructions (messages) from simulation and, according to system status, sends messages to physical equipment controllers. Once a task message has been sent, both executor and simulation wait for a "completed ok" message from controller. When executor receives "completed ok" message, it sends a similar message to simulation, and simulation knows that current task was completed. Simulator and execution modules communicate through a Task Initiation Queue (TIQ) and a Task Completion Queue (TCQ). Simulation uses TIQ to order executor perform specific tasks and receives completion messages through the TCQ. Son et al., [16] and Rao et al. [17] shows others SFS software use for controlling production process.

Digital models used in SFS are useful not only to control but also to design production plants layout. These models are usually stochastic-nature statistical distributions and are used to perform design variables analysis, control strategies and system performance estimation using commercial computer programs, for example: Arena™, AutoMod™, ProModel™, Tecnomatix Plant Simulation™, FlexSim™, Witness™, AnyLogic™, Process Model™, etc. Recently, these tools have been classified according to their popularity and tools [18].

Other interesting subject in Industry 4.0 is flexible production plants, it means "systems that allow changing product without high impact on costs either by sequence change programming" [19]. This flexibility can be understood as production lines flexibility or production processes flexibility. In general terms, if a good resources availability is achieved it is possible to maximize production process; This can be achieved adding new technology or using plant redistribution, and here SFS takes special interest because it let more easy decision making and it is much easier to achieve in a flexible LF where it is possible to reconfigure plant distribution. This is one of the greatest advantage in a LF for future research.

3. Digital Learning Factories implementation trends

A digital LF is an integrated IT environment where all real LF resources, processes and products are tracked on a digital model. Otherwise, virtual LF provide visual software tools trough Virtual Reality (VR) or Augmented Reality (AR) technology [20] to improve Digital LFs. Some LFs have implemented virtual games to evaluate students learning after training [21]. With these technologies, it is possible to carry out digital simulation, simulate tasks or evaluate alternative designs before production start [22].

LFs have become widespread in recent years, particularly in Europe [23], and have adopted many installation ways varying in size, scope, function and sophistication. However, all of they have main objective to improve students and industrial users learning experience. Abele et al. [24] present a right sounding classifying LFs worldwide according to:

Learning Factories for production process enhancement: They deal with lean methods and principles, such as just-in-time, line balancing, problem solving or work optimization.

Learning Factories for reconfiguration, production and plant layout design: They deal with reconfigurability related to plant layout design.

Learning Factories for energy and resources use efficiency: They deal with the relationship between energy consumption, resources and production.

Learning Factories for Industry 4.0: They focus on production digitization and Internet of Things (IoT) researching and technology transfer.

Learning Factory applied concept: They deal with knowledge triangle vertices integration: education, research and innovation.

Learning Factories for other purposes: For logistic optimization. For management and organization, automation technologies and sustainability.

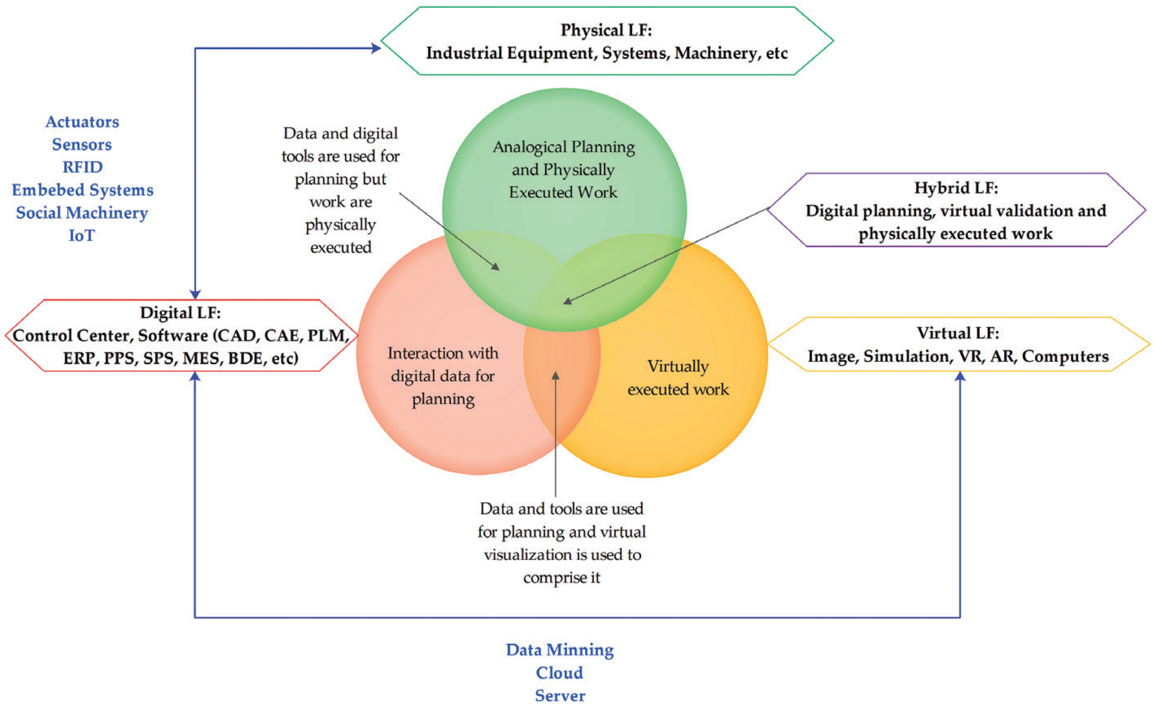

Figure 2. Physical, digital and virtual LF. ([24] p. 816).

This literature review shows there is an important trend towards facilities and production processes digitalization. Digital [25] and virtual LFs have been developed [26], even equipped with SFS software for material flow, tail and bottleneck analysis [27].

Figure 2 interrelation between infrastructure and physical interface in digital and virtual LFs. In this context, the SFS brings LF infrastructure to digital level.

First Colombian LF was inaugurated last September 27th, 2017. This LF is located at EAFIT University in Medellín City, and its main goal is to perform experiential learning practices with university and industry students to enhance their skills facing up new local production processes challenges, and help to transform conventional companies into smart companies [28]. This LF is equipped with SFS such as Tecnomatix Plant Simulation and FlexSim for production processes improvement. Thus, next step towards Industry 4.0 once this LF was inaugurated is SFS implementation in its own Digital Model.

4. How to use Learning Factories in plant layout simulation?

Plant layout simulation difficult due to the following aspects:

1. High time consumption in digital modeling: Large time amount must be invested in the digital modeling.

2. Digital modeling validation: Sometimes it is necessary to build expensive pilot plants or to carry out experiments in a section or all production line causing delays or stoppages. This is due to flexibility lack in the real plant to change its distribution.

3. Planning and experimenting: Experiments sometimes requires redesign experiment itself to input or output not considered variables, which in many cases involves rethinking production strategies.

Thus, a LF is a right scenario to learn how to carry out plant layout planning based on SFS because it solves mentioned drawbacks: test model, validation and experimentation. This subject has been studied in digital LFs as noted in Section 2, however, although several digital LFs are equipped with SFS software, it is not common to find publications showing SFS use in LF layout planning.

So far, there is a worldwide trend to immerse plant layout designers on real, digital or virtual simulated environments to help them decision making. However, even for experienced staff, simulation can be a very long process, and transmitting that knowledge to undergraduate, postgraduate students or even business people usually takes a long time, mainly due to people focus more on simulation model construction than system behavior understanding.

In an LF, plant layout simulation can be carried out following methods described by Banks [29] and Tako [30]; their contributions, contextualized to plant layout are summarized in **Figure 3**. They suggest contemplating six phases to reproduce discrete events during productive system operation; therefore, a student, instructor or professional (henceforth called analyst) should focus his attention on:

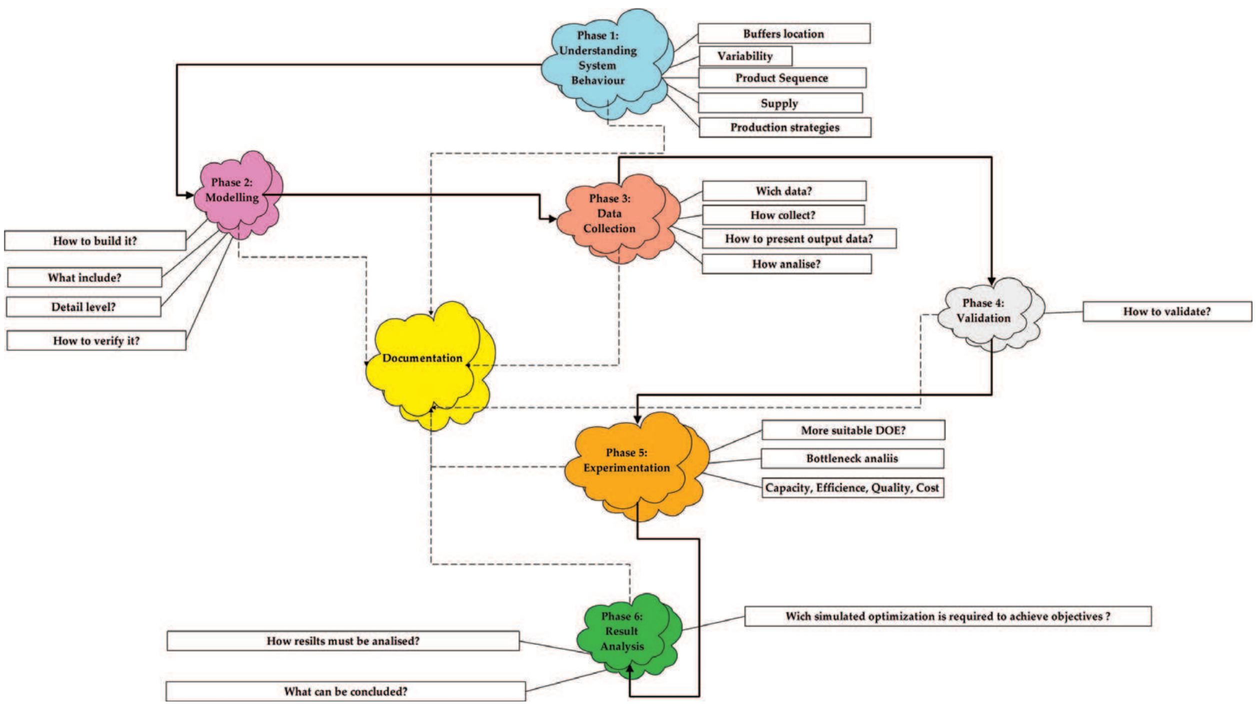

Figure 3. Methodology proposed by Banks and Tako for simulation adapted to SFS. ([45] p. 3528).

Phase 1: Understanding the problem. Understanding involved variables in system behavior is essential to propose an adjusted model regarding real system. It is important to understand variable appearing and disappearing, impact on production process and variability, even when production strategies are changed. This let to define clear objectives. Analyst must consider possible interest variables like: production time, assembly time, product quantity per time unit (capacity and efficiency), inputs and raw materials consumed per time unit, buffering time, etc. in this phase, a LF is a "Test Bank" to analyze how those interesting variables impacts plant layout.

Phase 2: Digital model building. Digital model main purpose is to represent adequately variables behavior. Sometimes it is necessary to make assumptions to simplify or complicate it, so there must have an adequate balance between easy use and high accuracy. Model must be detailed enough to capture as much information as possible according to study objectives. It is important to define detail level and construction method. LFs have limited size, and they allow build not very robust digital models with a high detail level and its construction does not demand excessive time. This aspect is an attractive alternative for future research because currently have low publications.

Phase 3: Data Collection: Information quality, and not quantity, allows more accurate analysis. LFs flexibility let to analyst adapt plant layout to data acquisition needs, considering product assembly sequence. In other words, relationship between production model and its critical variables differ from one type of product to another, however, the LFs can be adapted to certain types of products for data collection.

Phase 4: Model Validation. Validate a model is to obtain high degree of confidence to ensure correct predictions about process being simulated. There is no way to know which is most correct process to validate a model, however, experts consider relevant some guidelines for develop of a valid and credible model [31]:

- Use quantitative techniques to validate model components.
- Carry out sensitivity analyzes to determine most important factors in the model.
- Review simulation results to verify if they seem coherent. Here, again, LFs can be used. Given their resources redistribution availability, they are adequate to validate different simulated plant distribution models, becoming an interesting place for Engineers, Technicians and Managers, to evaluate decisions making impacts on productive practices.

Phase 5: Experimentation: Main experiments objective is to check whether the model complies with the assumptions and simplifications considered for validation. A good Design of Experiments (DOE) is crucial at this stage. It consists in determining tests and methodologies should be performed to obtain data and provide objective statistically evidence to answer the questions raised in phase 1 and clarify those process uncertain aspects that are being simulation object [32]. Once again, the LFs resources redistribution availability can be used to execute several experimental designs, expanding data collection opportunities portfolio.

Phase 6: Results Analysis. Finally, simulation results must lead to an appropriate decision making, either analyst consider that model is reliable and can use it to estimate the real one productive process variations or to discard it. Last case implies a new approach, a new analysis, and therefore anew simulation and a new digital model.

5. Shop floor simulation in industrial and academics scenarios

Layout planning can be categorized by static or dynamic environments. In the static layout approaches, material flow between machines is constant and an optimum layout is designed for a single time. On the contrary, if layout is evaluated and modified occasionally with respect to changes, research is categorized as dynamic. There are several plant simulation and discrete event simulation tools researching published, some of which have proposed design methodologies to structure, control and improve manufacturing processes [33, 34]. Below are some of them, both in industrial plants and training environments. The review of these cases cannot be considered complete but serves as a basis to demonstrate the capabilities of SFS in different scenarios.

5.1. Shop floor simulations in industrial production plants

Simulation based plant design and optimization techniques at industrial level have been implemented and developed several years ago. However, as mentioned in Section 1, there are many circumstances where uncertainty, interactions, objective functions or system constraints cannot be described using mathematical terms. In these cases, both, heuristic approach and SFS are often used to minimize some goals variables. For large dynamic plant layout problems, for example, some authors have suggested genetic algorithms-based heuristics solution methods [35].

Recently Pourhassan et al. [36] have presented mathematical models for relevant costs optimization during arrangement and re arrangement manufacturing facilities using genetic algorithms. A manufacturing system consisting of m machines processing n different products was considered. Products require m machines processing subsets causing material flow between they and eventually causing interference during material travel. Transporters are responsible to move materials between machines and there is plan divided into a several periods. Rate demand for each period is predicted and so material flow matrix is known in advance. Due to layout performance regarding to workflow is determined by number of possible transporters interference, researchers focused in to minimize material handling cost (MHC) and workflow interference as two inconsistent objective function:

$$Min\ Z_1 = \sum_{t=2}^{T}\sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{l=1}^{N} A_{tijl}*Y_{tijl} + \sum_{t=1}^{T}\sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{k=1}^{N}\sum_{l=1}^{N} F_{tik}*D_{jl}*C_{ik}*X_{tij}*X_{tkl} \tag{1}$$

$$Min\ Z_2 = Number\ of\ possible\ transporters\ accident \tag{2}$$

This model is subjected to decision variables:

$$\mathrm{X_{tij}} = \begin{cases} 1, \text{if machine } i \text{ is allocated to location } j \text{ in period } t \\ 0, \text{ otherwise} \end{cases}$$

and:

N = Number of machines/locations.

T = Number of periods in planning.

i,j,k,l = Index of machines/locations.

t = Index for time periods.

A_{tijl} = Cost to shift machine i from location j to l in period t.

F_{tik} = Total flow between machine i and k in period t.

D_{jl} = Distance between machine i to l.

$$\sum_{i=1}^{N} X_{tij} = 1, \forall i = 1, 2, \ldots N, \forall t = 1, 2, \ldots T \tag{3}$$

$$\sum_{i=1}^{N} X_{tij} = 1, \forall j = 1, 2, \ldots N, \forall t = 1, 2, \ldots T \tag{4}$$

$$Y_{tijl} = X_{(t-1)ij} * X_{til} \forall i, j, l = 1, 2, \ldots.N, \forall t = 2, \ldots T \tag{5}$$

Constraint Eq. (4) ensures that each machine should be in one position and constraint Eq. (5) ensures that in each position only one machine should be allocated.

Function Eq. (2) was evaluated through simulation models where a possible finite set of layout scenarios were reached using Design of Experiments (DOE). In this case, a case study with five machines in a vehicle part production system with a planning horizon of two periods was considered. This allowed researchers to find by regression a Z2 optimal function (a minimal number of possible transporters accident). This work shows how numerical simulation, DOE and regression can be applied to evaluate a manufacturing system and recommends considering dynamic layout problem where the flow between machines is stochastic.

So, it is important to study if LFs can reach this situation, like the one described above, in which material flow between machines is constant (static design) or modified occasionally with respect to changes (dynamic design). Again, flexibility of LFs can be useful for this purpose.

On the other hand, there are several investigations using only SFS for plan layout planning to arrange and re arrange plant distribution. Filip et al. [37], for example, used Witness® software to optimize production systems in a printed circuit board (PCB) assembly plant. After completing initial simulation process and a series of subsequent simulations, researchers were able to identify equipment with highest workload, and part quantity produced. They also determined most economical method to increase production, which was to include new intermediate buffers. After including the new buffers, overloaded machine workload was reduced by 16.7%, resulting an increase of 1804 finished parts. This is an example about how understanding problem and setting clear objectives can lead to very successful results using SFS, an interesting aspect to be considering in LFs implementation.

Siderska [38] used Tecnomatix Plant Simulation® to simulate plant distribution and logistics in wire steel production process. Because of simulation, process statistics showed that only 10% of cutting machines capacity was being used due to a bottleneck generated by tip forming machine. An improvement was suggested simulating an additional tip forming machine in parallel with the initial one, increasing production. However, no subsequent work to was published by researchers to confirming if proposed change was implemented in the real plant, so simulated model could not be validated.

Hnát et al. [39] implemented Tecnomatix Factory CAD/Factory Flow in Zilina Intelligent Manufacturing System (ZIMS) laboratory, at Central European Technologies Institute (CEIT) for logistics process design and control. They described how these tools can be used for logistics systems conceptual design, control and monitoring. These researchers emphasize that using these technologies, companies can avoid failures due to inadequate design of material flows using simulation to verify flow before implementation.

Kikolski [40] applied simulation models to study different production scenarios. With Tecnomatix Plant Simulation, author simulated a real production plant using known process technological data and related material flow data to production. Their experiments analyzed how batch size influences system efficiency. The first simulated scenario consisted of the current conditions of the plant, whose lots comprise series of 30 items and each component in the system. For Kikolski, simulation model is an excellent tool to verify processes performance and give a clear visualization about assumptions. Analyzes require availability of one initial already system to design and optimize their virtual models. Therefore, it is observed that has been proposed start from initial distribution by other authors in other environments than the LFs one. Kikolski insists about continuing work on modeling and simulation methods, since "computer simulation can become a useful and reliable tool to design and study manufacturing processes and can provide a basis for other studies aimed at using digital models within of production engineering".

Kliment et al. [41, 42] have worked with Tecnomatix Plant Simulation to simulate logistics processes and production process on several production plants. Again, these works have focused on problems detection before physical plant building, and no evidence was found indicating proposed changes implementation during the simulation stage, so actual plant validation does could not be confirmed.

In Colombia, production plants simulation studies have been carried out in specific sectors such as mining [43] and biofuels [44], but do not in manufacturing plants, do not reach an appreciable reproducibility and scalability level and not involve entire value chain since raw materials supply to distribution chain. In conclusion, although there is an international trend, in Colombia there are no published works in which production plants simulation has been validated along value chain, or their knowledge has been transferred to industrial sector by academic institutions and much less by LFs.

5.2. Shop floor simulations in educational environments

About educational environments, an experience to highlight is in Skövde University [45]. This institution has been able to demonstrate impact and importance of plants layout simulation on decision making. Its practical courses have competences focused on undergraduate students, engineers, technicians and managers, and contemplates strategies based on six simulation phases presented in Section 4.

Due to this training, there is more people using SFS to test new product variants and production flows in their companies and these people are agree about this training methodologies should be facilitated by software tools that can support fast modeling and advanced experiments in a practical way. This experience is an interesting alternative to be replicated in LFs and is an accolade to SFS use for plant layout design.

6. Conclusions and further research

Several authors have illustrated how SFS based production planning and control can be raised to business-level activities [46], therefore, decision making skills acquisition at all company levels becomes more important. Thus, EAFIT University Production Technologies Research Group (GITP) has started a LF implementation to become a focused digital LF towards Industry 4.0 development. In this LF, SFS will supports decision making in production planning and control; It intends become an innovation transmitter agent to students, technicians, engineers and managers. In this way, GITP proposes to establish a current state in SFS applied in LF to set medium term clear objectives, and as have been seen, information studied allows concluding:

1. SFS is an extensive research subject, and with enough technological maturity level to evaluate production systems behavior with digital validations. However, lack published works using SFS in LFs comprises a knowledge gap needed to be addressed.

2. There are not validated LFs digital models linking cause/effect relationship between production process and its critical variables.

3. Advantages mentioned in present work let to LFs be a suitable scenario for research in SFS towards Industry 4.0 digital plant. Given their size, flexibility and resources redistribution availability, they allow digital models construction and experiments running, and can be used for SFS implementation as a decision-making tool for production control and planning.

GITP has initiated experiential learning methodologies implementation in EAFIT University LF [47], and according to Guarín and Baena [48] "experiential learning is most used pedagogical development mechanism (…). However, not enough research has been done to systematically address experiential pedagogical structure in LF". Thus, and due to some authors have classified simulation as an experiential learning method [49], there is also a high interest in evaluating SFS role in teaching/learning process. This subject will be addressed in future research once LF digital model have been constructed.

GITP considers EAFIT university LF digital model construction is needed. This digital model must be supported with good DOE to validate production system behavior, either by stochastic methods as described in Section 5.1 or SFS software. Initially, it is proposed to define a product and implement its assembly in LF production line. A data collection at process initial state will let define critical variables which have more impact in time, cost and production quality. Later, using DOE, alternatives for plant redistribution will be proposed to optimize

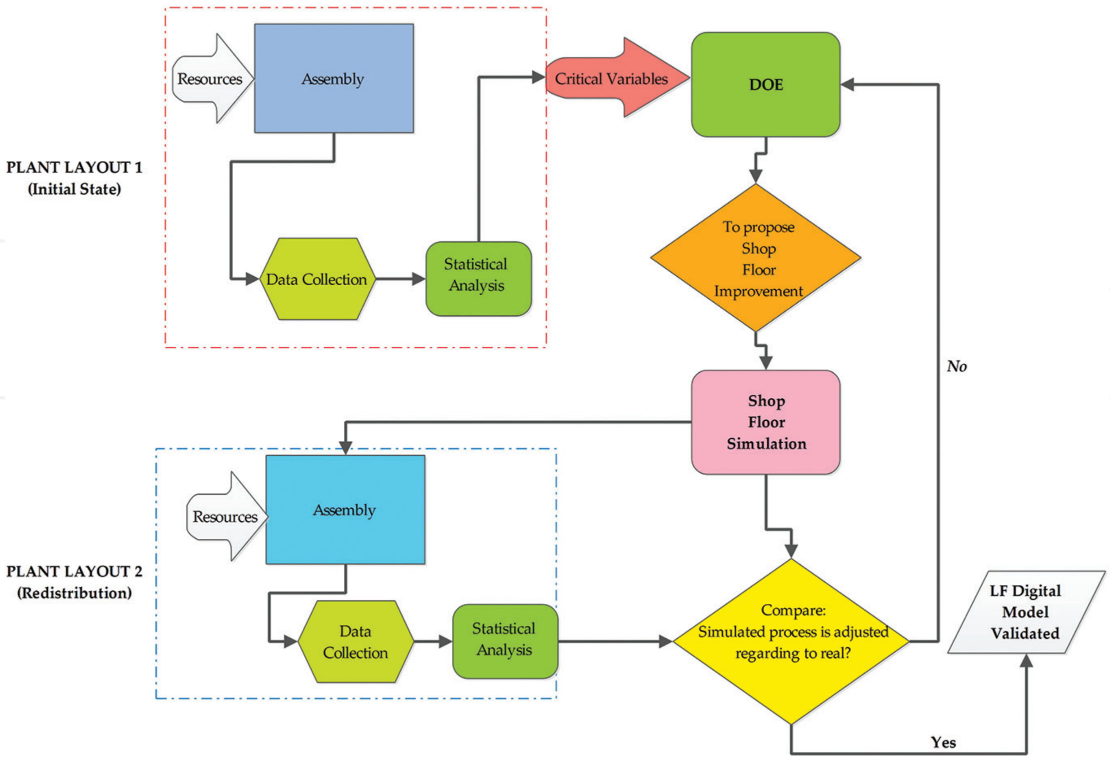

Figure 4. Proposed methodology for based SFS digital model construction in EAFIT University LF.

critical variables and verify statistically system response. These alternatives and information collected will be fed to an SFS software. Results obtained will be implemented by redistributing LF to validate digital model. See **Figure 4**.

As can be seen, there are several ways to take Learning Factories advantage for production activities research towards Industry 4.0, and shop floor simulation use and teaching for decision-making is one of the most relevant aspects to be investigated in the medium term, this is main reason to prepare this chapter.

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