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Supporting the lean journey with simulation and optimization in the context of Industry 4.0

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Abstract

The new industrial revolution brings important changes to organizations that will need to adapt their machines, systems and employees' competences to sustain their business in a highly competitive market. Management philosophies such as lean will also need to adapt to the improvement possibilities that Industry 4.0 brings. This paper presents a review on the role of lean and simulation in the context of Industry 4.0. Additionally, the paper presents a conceptual framework where simulation and optimization will make the lean approach more efficient, speeding up system improvements and reconfiguration, by means of an enhanced decision-making process and supported organizational learning.

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Keywords: Lean; Simulation; Optimization; Industry 4.0; Simulation-based optimization; Decision-making;

1. Introduction

In the last two centuries three different industrial revolutions have transformed the industry. The first one started with the mechanization of processes. The second revolution started a century later and introduced the concepts of mass production and electrification in the industrial processes. The third one, and still the actual one in most of the companies, is the introduction of digitalization in the industry. The automation of industrial processes and the

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introduction of computers to support manufacturing has been one of the main challenges for the companies in the last decades. However, the future is now in the fourth industrial revolution, the so-called "Industry 4.0" in Germany, "Smart factory" as the English term, "e-factory" in Japan or "Industry 2025" in Switzerland [1]. This revolution will be characterized not just by the technical realization but by the capacity of the companies to meet today´s and the future´s challenges [2].

Industry 4.0 can be defined as the industrial vision of having "people and things connected anytime, anyplace, with anything and anyone, ideally using any path/network and any service"[3]. The vision of this revolution is to move from a physical process supported by information technology (IT) to an integrated cyber-physical system (CPS) of production, where the physical world is fully integrated with the cyber world [4]. The Internet of Things (IoT) will be the enabler for networking the entire factory to form a smart factory [5]. The ultimate goal of Industry 4.0 is to provide companies with the flexibility to respond to the demands of end-markets, the increasing customization of products, shortened product life-cycles, as well as the increasing complexity of the production processes and products [6, 7]. However, some scientists think that in this scenario economies of scale will no longer be achieved. It will result on an increased pressure on productivity, even reducing it. These scientists call it the "productivity paradox" [8].

The speed in which the current breakthroughs are occurring has no precedents because it is happening in an exponential way, compared to the linear growth of previous revolutions [9]. The key technologies and development trends that are boosting those breakthroughs in industry 4.0 include the following: green IT, big data and analytics, autonomous robots/systems, horizontal and vertical system integration through new standards, cybersecurity, virtual and augmented reality, the industrial IoT, additive manufacturing, cloud technologies as well as simulation modelling [10, 11]. As a result of this new revolution, it seems that many changes will be needed in the actual companies: starting from the adaptation of individual machines and processes, the introduction of new technologies, the provision of new knowledge and competences to the workers and managers, as well as updated management system and practices.

A traditional, and probably one of the most widely extended, management philosophy is Lean. Lean is based on the Toyota Production System, and it aims to reduce waste in the companies while reducing the required time from customer order to delivery [12]. This philosophy is composed by different principles and tools and has been followed by many organizations, including manufacturing, healthcare, construction, etc. with more or less success in its implementation. However, lean has some drawbacks when it comes to analyzing complex systems and considering the variation and stochastic behavior of the real-world processes. These drawbacks will be especially critical in the upcoming scenario where the complexity of the production systems will increase. In order to cope with these, different authors have proposed to employ simulation to support lean [13-22].

Simulation as defined by [23] is a simplified representation of the real world operation over-time. Discrete-Event Simulation (DES) is the most popular simulation technique to support decision makers in manufacturing system design and improvement [24, 25]. Recently, optimization techniques are more and more commonly employed together with simulation to present optimal or nearly-optimal solutions to the decision makers and reduce the time-consuming experimentation phase of creating many different what-if scenarios with just employing simulation [26]. This approach has also been defined as intelligent simulation [24] or the "new simulation technology" [27]. It will be defined as simulation-based optimization (SBO) or simulation-based multi-objective optimization (SMO) hereafter.

Taking into account the changes that are expected to happen within this new industrial revolution, there are still many questions unanswered. What is the role of lean in this new context? And the role of simulation? This paper will try to answer these questions through a literature review, and will present a framework where lean, simulation and optimization are combined to speed up system improvements and reconfiguration, by means of an enhanced decision-making process and supported organizational learning. The literature review has been conducted in a traditional way according to the definition provided on [28], employing key words such as "industry 4.0", "lean", and "simulation" in different search engines, but also snowballing the results, following the references of the interesting papers as well as reading the papers citing them.

The paper is structured as follows: section 1 introduces the article; the link of lean and Industry 4.0 are described in section 2; Section 3 presents the future of simulation in the context of Industry 4.0; Section 4 identifies how lean, simulation and optimization can be combined in the context of Industry 4.0 and presents a conceptual framework; section 5 identifies some challenges and discussion; finally, section 6 concludes the paper.

2. Lean and Industry 4.0

Many organizations are striving to apply lean in their organizations in order to increase the efficiency in their processes. With the upcoming Industry 4.0, the question is if lean still will have a role or not in this new context. Different authors have presented scientific studies that point out in different directions. A framework analyzing the impact of the main elements of CPS of Industry 4.0 (data acquisition and data processing, machine to machine communication and human-machine interaction) in different lean principles and tools, as well as a case study where this framework has been applied is presented by [29]. These authors also defend that for a successful implementation of the concepts of Industry 4.0, an analysis of the initial situation of the companies should be taken into consideration. This also implies the analysis on how to combine the existing technologies with the new ones, as well as how the existing lean principles and tools can be supported by the techniques of Industry 4.0. A dilemma also arises when the approach of lean is to keep processes as simple as possible, given the fact that Industry 4.0 promotes the use of complex IT solutions to machines, humans and processes [29]. The authors conclude that “Industry 4.0 can stabilize and support the implementation of lean principles”.

Similarly, an interesting article discussing the relationship that lean and industry 4.0 may have is presented by [1]. The authors describe a lean approach with the aim to reduce dependency on IT, while industry 4.0 tries to integrate all the available information in the IT systems. The same authors point out that kaizen events may disappear in the future because blue collars will be substituted by machines. However, they highlight that the value added tasks performed by blue collar workers will not be to perform operations on the products, but to improve the system instead. They question whether the aim of lean being to reduce variability in the system (focused mainly on mass production) is opposed to the flexibility that characterizes industry 4.0 (focused on mass customization). The economic aspect inherent to the investments needed by Industry 4.0 solutions is also raised by the authors, who question the viability of the Industry 4.0 approach of getting high flexibility to low cost. The paper is concluded stating that Industry 4.0 will make the lean approach more flexible and “whether it makes it faster, smoother, and more stable and accurate has to be proven” [1].

Others defend a renewed Lean Automation concept based on Industry 4.0 technologies [30, 31]. This concept began to be popular in the 1990s and combines automation technology with lean. It was first introduced by Ohno who called it autonomation [32], where employees supervise automatized processes. This concept corresponds perfectly with the approach of Industry 4.0. Therefore, it seems that combining the technological advances of Industry 4.0 with lean, will improve the benefits of lean in the companies. Examples include the digitalization of the Kanban method or the integration of automated order management systems from the ERP to u-shaped assembly stations (Chaku Chaku lines) [30]. It will be especially interesting to employ Industry 4.0 solutions where simple lean methods do not fulfill the requirements [30]. Furthermore, the implementation of Industry 4.0 solutions will be eased in companies which have applied the standardized and waste elimination approach of lean [30]. The same authors present some use cases of this combination for: 1) smart operators, where Andon could be reinforced by the use of smartwatches by employees, or continuous flow could be supported by augmented reality systems to aid employees; 2) smart products, where the products could store information about their production details, eliminating the need to collect data to create e.g. a Value Stream map; 3) smart machines, where Industry 4.0 could support a flexible production with modular working stations and standardized IT via “Plug and Produce”, reducing setup times (SMED); and 4) smart planners could allow dynamical production systems where CPS could negotiate the optimum cycle times adapted to the individual products to produce in each moment, and still achieving a continuous flow, enabling lean to be applied also in job shop production. A similar classification is provided by [33] in which three different paradigms of Industry 4.0 and similar examples of cases studies for smart product, smart machine and augmented operator, are presented.

According to [31], Industry 4.0 solutions will support companies become lean without “striving-for-lean” efforts. The authors present ten dimensions of lean based on supplier, customer, process and control, as well as human factors. They also identify the main challenges for each dimension, such as improper track of goods, missing data, inability to track process variations, human experience-based process variations, etc. and possible solutions via Industry 4.0 technologies, such as better communication and synchronization of data, wireless tracking of goods, self-optimization and machine learning, improved man-machine/machine-machine/workpiece-machine communication, etc.

This review suggests that in the future lean, far from disappearing, it will still be a key philosophy to support companies in becoming more efficient. Industry 4.0 solutions will support its implementation in companies, even overcoming some of the nowadays existing obstacles for lean implementation.

3. Simulation and Industry 4.0

According to a study about Industry 4.0, the three most relevant production characteristics in the future will be to deal with system complexity, to have capacity for innovation and flexibility [34]. According to [33], six different design principles could be derived from the above characteristics: interoperability, virtualization, decentralization, real-time capability, service orientation and modularity. Virtualization is referred to the virtual copy of physical objects. In the same context, Virtual factory as defined by [35] is the "integrated simulation model of major subsystems in a factory that considers the factory as a whole and provides an advanced decision support capability". DES is considered by the same authors as one of the key technologies to create this virtual factory. The virtual factory has also been called digital twin, virtual copy or digital copy by other authors, and is according to [36] and [10] the next modelling, simulation and optimization paradigm. This new paradigm will include the extended use of simulation not just in the design and planning phases, but in the entire lifecycle of the product [36].

The future developments of modelling and simulation, changing from stand-alone simulation models to the digital twin for decision-making support, are identified by [10], [11] and [37]: 1) the connectivity and integration of simulation with other internal and external data (real-time and big data) and information systems (e.g. MRP, ERP); 2) multi-level simulation models, including physical modelling; 3) models will be smart, self-correcting, learning systems that are able to adapt their behavior depending on changing conditions and past experiences; 4) near to real-time simulation models, shortened cycle model building and semi-autonomous problem solving; 5) to couple simulation to evolutionary knowledge databases (which will continuously learn and grow); 6) simulation will provide the company employees with a tool for decision-making with no specialized training needed; 7) supportive analytical tools will be available and connected to the simulation tools so the decision makers will have all the evaluation options at hand to take the best decisions. These future goals will pursue the creation of a robust simulation infrastructure to aid decision makers at all levels of the organization in order to offer a clear view of the status of a system, evaluate improvement and design options and have a real-time view of the changes made at any level of the company.

Some other research is related to the importance that a more integrated link between DES with virtual reality and augmented reality will have in the future [11]. Some others also present the Internet of Simulation as an emerging extension of IoT, being a convergence of the need for increased co-simulation for virtual engineering and the application of internet technologies in simulation [38].

In the last decades, simulation has developed from a tool for experts to a standard tool in an engineers' portfolio [10], and according to the performed review, it will become even a more important tool in the future, becoming a key technology in the context of Industry 4.0.

4. Combining lean, simulation and optimization in the context of Industry 4.0

Taking into account that both lean and simulation will have an important role in the future of manufacturing, even in the Industry 4.0 context, it seems important to analyze how their combination can support the companies. Several authors have identified how lean and simulation having the same objective of supporting the companies to perform better, should be combined [13-19, 22, 39, 40]. Although most of them focus on how specific lean tools such as VSM and JIT can be combined with simulation, the authors in [22] present a framework where lean, simulation and optimization are combined for educational, facilitation and evaluation purposes. These purposes will still remain actual in the context of industry 4.0.

Some limitations of the lean approach in relation to the new changes in the market demands are identified by [30], including: 1) strong deviation in market demands versus required levelled capacity utilization; 2) lean was mainly designed for mass production, not for mass customization; 3) lean does not take into account the new capabilities that modern IT offers. Additionally, the trial and error approach inherent to lean (or improvement Kata) to continuously improve the processes requires a high amount of time to achieve the required improvement status [22], which does not match the future requirements for shorter product life cycles and therefore the needed quick changes in the production lines. Furthermore, the future production characteristics related to complexity, to have capacity for innovation and flexibility [34] can be easily tackled by simulation and optimization techniques. This is not the case of lean tools such as VSM that have limitations to handle variation and the stochastic behaviour of complex systems. However when building those simulation models, lean principles still need to be taken into account, so the combination of both of them will be crucial.

Simulation and optimization techniques can support quicker and more effective production systems' design and improvements by providing the decision makers with better alternative scenarios. As simulation is not an optimization tool by itself, the combined use of simulation and optimization, the so-called Simulation-based Optimization (SBO) or Simulation-based Multi-objective Optimization (SMO), in the case of having multiple objectives, is a better approach [26]. SMO will offer the decision makers with trade-off solutions between several conflicting objectives [41]. To be able to take quality decisions, the more knowledge and understanding on how the system performs, the better will be the decision taken [42] and SMO can offer this knowledge to the decision makers. According to [1], a muda or waste free approach requires an optimal solution achievable by multi-objective optimization.

Even if nowadays the development of simulation models takes time, once an initial version of the model is built, to make changes takes relatively little time, and definitely reduces the required time to build new system and improved designs compared to the use of lean tools such as VSM or continuous improvements via the improvement Kata or problem solving Kata approaches as defined in [43]. This required time to build the simulation model will even be reduced in the future according to [37]. Additionally, one of the most difficult tasks when building a DES model is to gather the needed amount of data. Usually, not all the required data is available in the companies and it is an arduous task to collect and analyze it. However, in the context of Industry 4.0 this will no longer be a problem and the required time to build simulation models will be considerably reduced. Therefore, the needed flexibility of future complex production systems taking into account the lean principles can be effectively designed and evaluated via SMO.

On the other hand, SMO can be employed as an educational tool to support the employees of the company to understand the impact of the changes on the production lines before implementation and even to support the understanding of the impact of the lean principles. This will be even more interesting in the context of Industry 4.0 where the workers will need new competences to answer to the needs that the new industrial revolution will bring. They will therefore need to acquire new knowledge. SMO can speed-up the coaching kata process, testing the needed changes in the production system and analyzing its impact in a virtual environment rather than in the real one. This approach supports the development of the personnel in the organization, a principle inherent to lean's respect for people.

The possibility of SMO to design and evaluate production changes in the virtual environment can also include the sustainability goals of the companies. Environmental indicators can be taken into account within the SMO study, as suggested by [44].

A case study where the concepts of lean and SMO have been applied in the context of industry 4.0 is presented in [29] where a Just in Time cyber-physical delivery application has been shown and also in [45] where the authors highlight the importance of combining SBO and lean supported by Industry 4.0 solutions. However, a standardized framework is missing. This framework is needed to provide the companies with a standard to start working with lean and SMO already now, as one of the first steps towards introducing Industry 4.0 solutions.

The following Figure 1 presents a conceptual framework where the collaboration opportunities for lean and SMO are identified. Lean philosophy influences the SMO and post-optimization processes (e.g. data mining), as well as how the organizational processes are run. The culture of the organization is also influenced by this philosophy. Lean tools may complement the SMO process in different stages. Additionally, SMO can become a new tool within the lean toolbox. These tools are employed by people to run the organization´s processes and also support decision-making when improving and designing systems. SMO will provide a knowledge-driven analysis for this purpose. Additionally, it may be helpful to facilitate education in how specific lean concepts work (e.g. pull vs. push, Kanban, etc.) and even to speed-up the training provided by coaches to the learners, reducing the coaching cycles and therefore the time required for this purpose. The quality of the decisions made according to this approach will impact in the performance of the processes, and therefore, in the overall organizational performance.

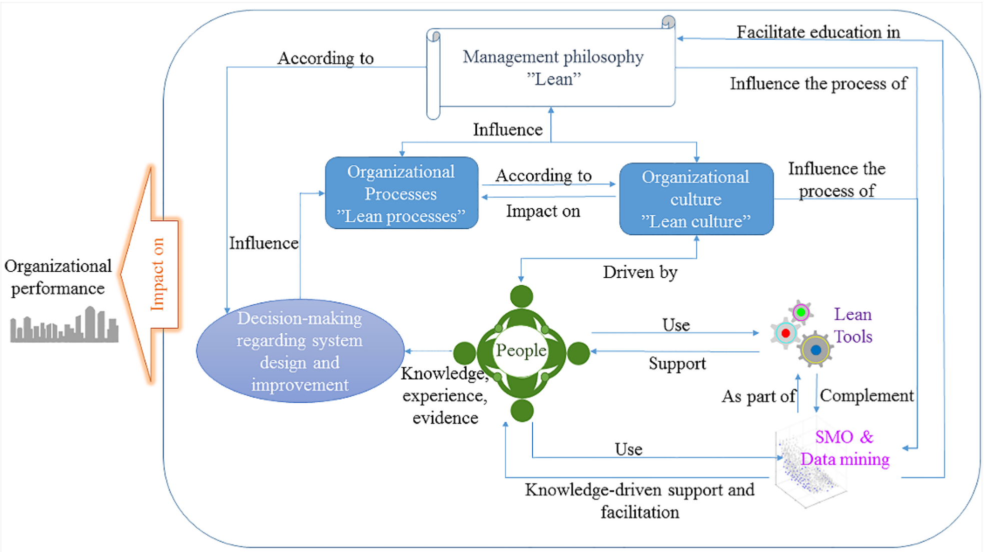

Fig. 1. Conceptual framework combining lean and SMO.

A handbook has also been written by the authors to describe in detail this framework. One of the important aspects highlighted in this handbook is the need for collaboration between the personnel with lean knowledge and the simulation engineers during the SMO process. This is even aligned with the lean principle of respect for people. Moreover, a maturity model has been presented in [40] to support the companies in the identification of their maturity status in lean and SMO and recommendations to evolve to more mature levels. The details of this framework have been designed to support actual companies, however, it will probably need to be adapted in the future to the new changes that Industry 4.0 will bring.

5. Discussion and identified challenges

Industry 4.0 is still in its conceptual phase [10] and its implementation and adoption by the industry will take time. Some authors even talk about evolution rather than revolution and doubt about its future [1]. The virtual factory or digital twin does not fully include the technologies available today. There are still many challenges regarding mainly: real-time data availability, low standardization and decentralization of data acquisition, lack of motion data and data security [46], as well as factory systems are not fully interlinked [11]. Also the validation and verification of simulation models in real time will be a challenge in the future [10, 11]. However, it is not a matter of if Industry 4.0 will become a reality, but when it will happen. The manufacturing industry is taking the lead and probably other areas such as healthcare will follow in the future. It will probably take more time to be implemented in SMEs where a high percentage is still even unaware of the term Industry 4.0 [5]. Even for the implementation of lean, the reality is different for large companies or SMEs, where lean is still not so extended among SMEs [47, 48]. The use of simulation or SMO is even less employed in SMEs and even many large companies do not include it in their toolbox yet. To gather the data required to build a reliable simulation model may also be a challenge for SMEs. Furthermore, the combined use of simulation and optimization is still not sufficiently employed to take advantage of real-time models [46]. Additionally, the implementation of Industry 4.0 involves an important investment in the acquisition of new technology and its implementation. So especially SMEs may be reluctant to adopt this approach. Authors in [1] even point out a risk that mass customization will bring for SMEs, as big companies will start dealing with smaller customized demands usually being the niche of SMEs.

From a workers' perspective, according to [9], Industry 4.0 will promote the elimination of routine tasks where the workers will need to focus on quality assurance, creative work and will also have more freedom to take decisions and regulate their own workload. This is also in line with the statement by [33] that augmented operators will be supported by mobile and context-sensitive user interfaces and support systems, allowing them to become decision makers and flexible problem-solvers in a growing complexity production. However, according to [9], these promises are still not a reality, and in many companies they are far from being achievable. Additionally, the changes in the technologies just by themselves will not aid any gain in productivity, an organizational change will be needed to support the use of the new technologies included by Industry 4.0. An investment to adapt the competences of the workers will be needed to embrace the new advances that this industrial revolution will bring. This is in line with the principle respect for people key in lean, where the personnel has to be developed with the aim to maximize individual and team performance. Moreover, this key principle includes the need to understand and build mutual trust among the stakeholders of the organization (customers, personnel, suppliers and shareholders) which will need to be sustained even in the context of Industry 4.0.

6. Conclusions

This paper describes the future role that lean and simulation will have in the context of Industry 4.0. The performed review concludes that lean principles will still be crucial to ensure the efficiency of the companies of the future. Similarly, simulation will be a key tool within the Industry 4.0 solutions to facilitate the evaluation of improvements in a highly complex and dynamic scenario. Moreover, a conceptual framework where lean, simulation and optimization are combined has been presented where the advantages of this combination are highlighted within the context of Industry 4.0. This combination will enhance the traditional decision-making process, will speed-up system improvements and reconfiguration and will support organizational learning. This framework can be established as one of the first standards for companies where a traditional approach such as lean is combined with more advanced techniques such as SMO for different purposes: evaluation, facilitation and education. An industrial handbook has also been produced as a result of this research, in which a detailed description about how to combine lean and SMO is explained.

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