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# LEAN, SIMULATION AND OPTIMIZATION: A WIN-WIN COMBINATION

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## ABSTRACT

Lean and simulation analysis are driven by the same objective, how to better design and improve processes making the companies more competitive. The adoption of lean has been widely spread in companies from public to private sectors and simulation is nowadays becoming more and more popular. Several authors have pointed out the benefits of combining simulation and lean, however, they are still rarely used together in practice. Optimization as an additional technique to this combination is even a more powerful approach especially when designing and improving complex processes with multiple conflicting objectives. This paper presents the mutual benefits that are gained when combining lean, simulation and optimization and how they overcome each other´s limitations. A framework including the three concepts, some of the barriers for its implementation and a real-world industrial example are also described.

## 1 INTRODUCTION

Companies and public organizations need to continuously innovate and improve their processes in order to remain competitive in a global and dynamic market while offering the best service to their customers. There are multiple philosophies, methods and tools that are supporting these organizations with that aim. Lean, Six Sigma, and Theory of Constraints are probably the three most prevalent philosophies adopted on a worldwide basis.

Lean concept evolved in Japan from the Toyota Production System (TPS) after the Second World War. Based on a MIT study on the huge success of Japanese automobile manufacturers, Womack, Jones, and Roos (1990) originally used the word "lean" to describe the Japanese manufacturing philosophy with Toyota as the leading company. Since then, lean has become widely adopted in manufacturing companies but also in healthcare and service organizations with more or less success in their results. A plethora of definitions about what lean is can be found in the literature, but according to Liker (1996) "it is a philosophy that when implemented reduces the time from customer order to delivery by eliminating sources of waste in the production flow".

Simulation techniques started their earlier development in the late 1950´s and have now flourished to become a decision-aiding tool for different kind of organizations. As defined by Banks (1998) simulation is "the imitation of the operation of a real-world process or system over time". Simulation can evaluate several alternatives or so-called simulation scenarios under a variety of conditions with the aim of improving and designing processes. In this article when referring to simulation, the focus is on Discrete Event Simulation (DES). Recently, the integration of meta-heuristic optimization with simulation models, the simulation-based optimization (SBO) approach, has endowed simulation to be a powerful technique to identify and evaluate the best possible system improvements and also to eliminate much of the time-consuming experimentation task (April et al. 2004). Law and McComas (2002) described simulation-based optimization as the "most significant new simulation technology". Moreover, when there are multiple conflicting objectives, then simulation-based multi-objective optimization (SMO) can be applied. This paper is focused on meta-heuristic multi-objective optimization.

Taking into account that lean, simulation and optimization are all aiming at system improvement, it is surprising that in practice they are seldom combined. This paper presents the mutual benefits that can be gained when combining simulation and optimization with lean. A framework for this integration as well as a simplified process are presented and some of the barriers that may appear when implementing this approach have been identified. The structure of the paper is divided as follows: a literature review, a framework, a simplified process and the benefits of combining lean, simulation and optimization are presented in Section 2. Section 3 describes the barriers. How simulation and optimization were used in a real-world lean improvement project is included in Section 4. Conclusions and future work are presented in Section 5.

## 2 COMBINING LEAN, SIMULATION AND OPTIMIZATION

### 2.1 Background and Literature Review

Plenty of articles can be found in the literature related to how specific lean tools have been complemented or tested with simulation, such as Value Stream Mapping (VSM) and Just in Time. But it has not been until the last decade that more authors have started to identify the benefits that can be gained when combining lean and simulation as a new concept and not focusing on specific tools. It is surprising that given that they have a common motivation, this combination has not been discussed more often in the literature (Robinson et al. 2012).

Standridge and Marvel (2006) define the deficiencies of lean and how simulation can overcome those deficiencies. The same authors later on present a simulation-enhanced lean process, identifying the future step validation as a key step in the process (Marvel and Standridge 2009). Adams et al. (1999) present a typical continuous improvement process identifying how simulation can support each of the process steps. Robinson et al. (2012) describe from a theoretical and empirical perspective how DES and lean are complementary methodologies. They also present a three modules framework called SimLean where simulation is used to educate in lean, facilitate the understanding of different lean alternatives and experiment and evaluate different scenarios. Related to the educational module, Schroer (2004) presents how simulation can be used to understand the concepts of lean manufacturing. Similarly, Detty and Yingling (2000) present simulation as a technique to evaluate whether to apply or not to apply the shop-floor principles of lean manufacturing.

Ferrin, Miller, and Muthler (2005) identify how simulation provides a reduction of variation and is a good fit for Lean-Six Sigma. Jia and Perera (2009) conclude their paper stating that they want to define a framework of how to embed simulation into lean and Six Sigma projects. Following a similar approach, El-Haik and Al-Aomar (2006) present a simulation-based Lean Six-Sigma approach in their book. They define a DMAIC (Define, Measure, Analyze, Improve and Control) process where lean tools are integrated and where DES plays a key role in each of the phases. They also present an optimization stage by statistical means as part of the Analyze phase of DMAIC. Miller, Pawloski, and Standridge (2010) state in their paper that quantitative analysis tools such as DES make a lean transformation more precise. They present three case studies where the use of simulation and mathematical optimization within lean and green strategies are highlighted. Although these two articles pointed out the use of optimization techniques within a lean strategy, there cannot be found many articles in the literature addressing the combination of lean, simulation and optimization.

### 2.2 Simulation Supporting Lean

There is no question about the benefits of applying lean for system improvement, but it still has weaknesses. Many authors have proposed simulation as a tool to complement lean to cope with these deficiencies (Marvel and Standridge 2009; Standridge and Marvel 2006; Ferrin, Miller, and Muthler 2005; Adams et al. 1999; Robinson et al. 2012; Jia and Perera 2009; Miller, Pawloski, and Standridge 2010).

While lean makes strong focus on identifying and reducing waste, variability as the major source of waste is not addressed adequately (Standridge and Marvel 2006). This is because lean is inherently a deterministic method. Authors in manufacturing sciences have stressed that both random and structural variations have to be tackled in order to improve the performance of any system (Hopp and Spearman 2008). Many decision variables often found in manufacturing and healthcare systems are random variables. Simulation can handle variation and work with probability distributions.

At the same time, lean emphasizes “trial and error” and “experiments” or one step at a time process as defined by Rother (2010). This limits the opportunity to find possible interactions between components of the system (Standridge and Marvel 2006, Marvel and Standridge 2009) and it does not rely on any methods or models to minimize or eliminate sub-optimization. Using simulation to quantify the benefits that can be expected from implementing system improvements and comparing the actual system with its future performance can assist the organization to take the crucial decisions (Abdulmalek and Rajgopal 2007, Marvel and Standridge 2009) and avoid failures in the implementation of lean management principles (Anand and Kodali 2009). Additionally, errors when implementing an incorrect future state can be costly and result in unnecessary waste making a lean implementation unsustainable (Miller, Pawloski, and Standridge 2010).

Simulation on the other hand, can offer a systemic view and provide the analysis of how different changes in one component affect the system. When the system is rather complex to analyze due to the number of existing interactions, the amount of people involved, the variability level, the size of the system or if it is a non-existing system, then simulation is a better tool for identifying where and how to improve the system. It can help to explore, discuss and re-test scenarios that are non-intuitive or non-existing and probably would have been very difficult or impossible to find without simulation (Miller, Pawloski, and Standridge 2010).

Besides the role of supporting lean to overcome its deficiencies, simulation can also act as a tool to complement lean in other stages of the process. Based on the SimLean approach defined by Robinson et al. (2012), we propose that simulation can also support lean with the following purposes (see Figure 1):

- *Educational purpose*: Different authors have agreed in the educational function of simulation to teach lean concepts (Robinson et al. 2012; Schroer 2004). Additionally, it can be a way of training personnel in how the company´s processes operate (Adams et al. 1999).
- *Facilitation purpose*: As defined by Robinson et al. (2012), during a lean discussion an aggregated simulation model can be used as a dynamic process map to make understandable a process and to analyze different alternatives. It certainly will offer better information than a static map, and therefore be used as an alternative or complement to a lean tool such as Value Stream Mapping.
- *Evaluation purpose*:
    - *Evaluating the current state*: A simulation model developed for this purpose can give a systemic and dynamic view of the process and at the same time offer analytic and quantitative outputs. As defended by Adams et al. (1999) this is one of the key roles of the use of simulation in continuous process improvement. In the lean practice, this assessment is done more in a descriptive and qualitative way than in an analytic and quantitative one (Marvel and Standridge 2009).

- *Evaluating a future state/target condition*: Different alternatives can be analyzed with simulation in order to test if the detected opportunities and changes are feasible to implement, what would be the impact of this implementation in the process and to rank the best opportunities to implement (Adams et al. 1999; Marvel and Standridge 2009; Robinson et al. 2012). It can also quantify in a pre-lean stage the impact of adopting different lean manufacturing principles (Detty and Yingling 2000). Moreover, it offers even a more important advantage when non-existing processes have to be designed and evaluated. Petersson et al. (2009) disagree and explain in their book that the use of simulation has the problem of comparing solutions without questioning the potential that lies in the improvement process. The proposed approach in this paper suggests that simulation should not stop the continuous improvement of lean but rather support it.
- *Evaluating the implementation*: Once a future state is validated and the decision about what to implement is taken, the implementation stage is started. Lean plays an important role in that stage. But simulation can support the evaluation phase of that implementation (Adams et al. 1999). In case the target condition has not been achieved, the simulation model can be used to analyze the reasons and what additional changes need to be implemented.

Consequently, integrating simulation as key tool of the lean toolbox would help organizations improve their performance in a more efficient way. As defended by Miller, Pawloski, and Standridge (2010), lean alone can make a great contribution to companies but supported by simulation it becomes even more powerful.

Figure 1 presents a simplified view of the proposed framework in which lean, simulation and optimization are combined (a more detailed framework is under development). Each one of the purposes described above are shown in their correspondent application stages (referred to: a pre, during or after a lean event). Lean principles are presented as the general frame which embraces the whole framework. The simulation purposes are represented according to the model aggregation level required.

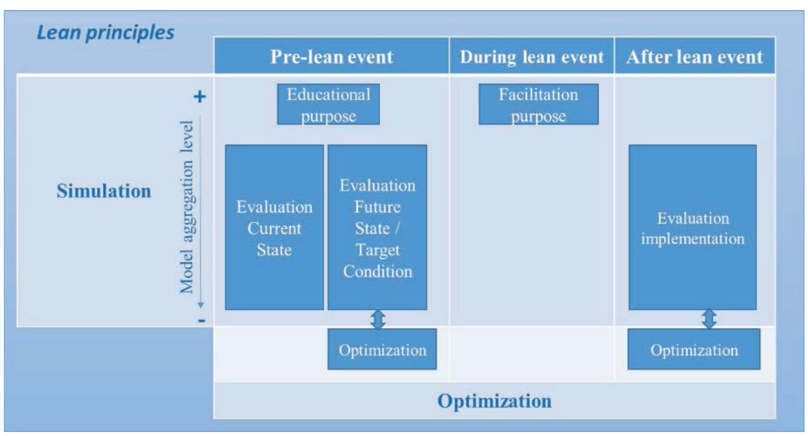


Figure 1: Simplified view of the framework combining lean, simulation and optimization.

## 2.3 Lean Supporting the Simulation Process

The traditional simulation process does not seem to involve any consideration to lean. Simulation engineers and project leaders do not necessarily have knowledge about lean. Furthermore, the simulation project objective does not have to be consistent with the lean principles. This lack of lean consideration during a simulation process could be tackled by including an experienced lean manager. But in practice, the problem is that simulation engineers and lean experts are usually from different departments and rarely interact with each other. Additionally, the project team is just waiting to receive the simulation results in order to continue with the project plan, without interacting with the simulation engineers in the process. A company which is trying to become lean, should also pay attention to the simulation projects and ensure that the project objectives will follow the philosophy the company is trying to implement. Not doing this could partly jeopardize the lean development or the viability of the simulation solution. It would be even more effective if people with lean background would be involved in the most important stages of a simulation process, e.g. taking into account the lean principles when defining the target condition and which scenarios to test in the simulation model as presented in Figure 2. Moreover, tools used in a lean project such as VSM and the Ishikawa diagram can be an input for the stages of process mapping and definition of decision variables, range and constraints of the simulation and optimization respectively (see Figure 2).

The following Figure 2 shows in a simplified way the steps to perform in any lean or simulation project. This process visualizes how lean, simulation and optimization are supporting each step of the process.

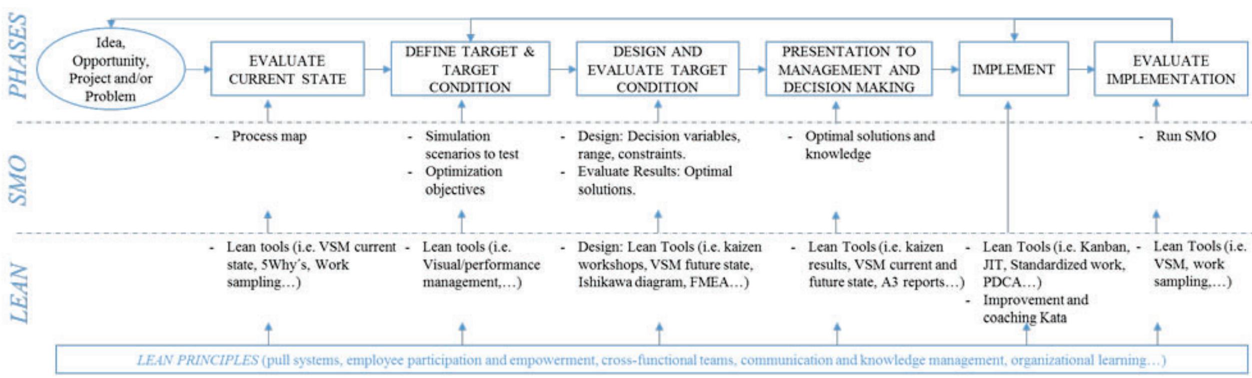


Figure 2: A simplification of the process followed by any lean and simulation project, where lean, simulation and optimization are combined.

When analyzing real-world cases, the authors realized that the whole knowledge extracted by simulation engineers during a project is not shared with their stakeholders. Interestingly, the perception in the stakeholders is that they got all they needed. From a lean perspective this is a waste because there are improvement alternatives that are not taken into account and system understanding that is never shared. This loss is mainly due to the usual collaboration scheme of simulation engineers with their stakeholders who just interact with the model once it is finished. A more collaborative process would provide a better developed model due to the insight gained by the simulation engineer during the process and additionally, the purpose of the model would be the one defined by the stakeholders and not the one perceived by the modeler (Baldwin, Eldabi, and Paul 2004). Which means that the teamwork approach is also something that must be considered in a lean enabled simulation process. This collaborative approach should be a key issue in the phases of evaluation of the current state, definition, design and evaluation of the target and target condition and the presentation to management and decision making. After the implementation, if the target condition hasn´t been achieved, the collaboration should be maintained in the evaluation of the implementation stage.

Different soft concepts of lean such as employee empowerment, organizational learning, continuous improvement and knowledge management may also have an important influence in the simulation process. People working in an organization which has implemented these management practices will definitely perform better. This includes the simulation engineers and it will affect the way the simulation process is done nowadays towards a more participative process where the knowledge is shared, the opportunities are not lost and the outcome of the process is more valuable. Figure 2 shows how the lean principles can be part of each step of the process.

On the other hand, there are different situations where it is not recommended to use simulation for process design and improvement (Banks and Gibson 1997). In these cases lean tools may be a good alternative to be applied. A correct lean and simulation combined process should be able to identify when to apply the different available tools and principles.

### 2.4 Why to Consider Optimization? Optimization Supporting Lean and Simulation

Lean, simulation and optimization are rarely discussed together. Optimization as a recent technique compared to the history of simulation and lean, has become a common approach in combination with simulation in the past years, but still lean is not included in this approach. El-Haik and Al-Aomar (2006) include a simulation optimization by statistical means in their simulation-based Lean Six-Sigma roadmap. Depending on the type of problem to analyze, there are different optimization methods that can be used in combination with simulation, of which several are presented by Figueira and Almada-Lobo (2014). This paper is focused in meta-heuristic optimization which is a flexible approach to examine any solution space and it is characterized by quickly achieving good quality solutions, therefore it has usually been used in combination with DES (Figueira and Almada-Lobo 2014).

The shortcoming of both lean and simulation is that they usually need a large amount of time in order to achieve an optimal configuration and still optimality is not guaranteed. Since lean and simulation are not optimization tools by themselves, it seems that to include optimization would provide a better process and therefore, a better outcome. Combining optimization and simulation tools allows decision-makers to quickly determine optimal (or nearly optimal) system configurations, even for complex integrated facilities. Consequently, the integration of optimization together with simulation is necessary if the optimal range of solutions for the given input is wanted. Moreover, if there are multiple objectives to be analyzed at the same time, then SMO is the preferred approach. SMO facilitates the search for trade-offs solutions between several conflicting objectives (Deb 2001). As defended by Miller, Pawloski, and Standridge (2010) taking into account the aims of lean, to include quantitative analysis tools such as simulation and optimization in lean companies have a positive impact.

Rother (2010) defends the one step at a time approach. Although it surely is a very useful method for improvement of existing processes and simple to apply, it does not allow to explore and test different scenarios, concepts and obstacles in advance which seems to be a downside of the Kata concept (Pehrsson 2013). This also leads to the criticism that Lean is only an art of manufacturing and its ease of acceptance among industry is due to the less scientific approach (Ignizio 2009).

Figure 3 describes the Kata view where the gray or unknown zone is the territory through which a continuous improvement team needs to navigate to reach the target condition. After implementing each improvement, the team evaluates whether they are going towards the target condition or not and if they have to step back and try something else instead. Of course, there is an important learning phase in the process but it can really take time to achieve the target condition and still its achievement is not ensured. The method is also limited if non-existing scenarios have to be evaluated. Instead, if simulation techniques are used, different scenarios can be tested with the aim of reaching the target condition. Improved scenarios could be designed (for example the discontinuous vs. the continuous line in Figure 3 below), but still there is no certainty that the scenario is the optimal one to achieve the target condition. There may be a gap between an improved and the optimal scenario. That´s why in this case there is still a level of uncertainty or gray zone, although smaller one than in the lean applied alone process.

Finally, if the optimization is included, the set of optimal solutions based on the given inputs and defined constraints will be provided in order to achieve the target condition. Then it is up to the decision maker to choose which one is the best and can be implemented. Optimization is not going to give us just the optimal solutions, but it is also going to provide knowledge about what not to do or which steps should be avoided (represented with an “x” in Figure 3) because they go against the defined goal.

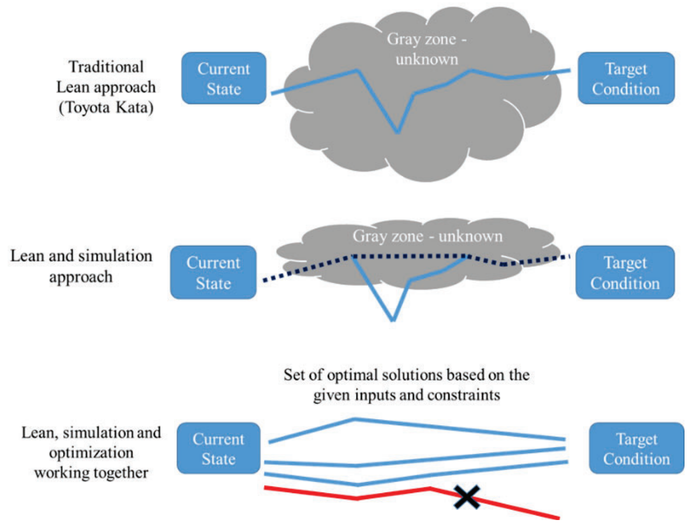


Figure 3: Comparison of the Toyota Kata approach (Rother 2010) vs. integrating simulation and optimization with lean.

Taking into account what has been defined in the previous section (see Section 2.3), optimization can support simulation in the purposes of evaluating a future condition and evaluating the implementation (see Figure 1), in both of them finding the optimal set of solutions.

To conclude, including optimization together with simulation in the lean package, will support the decision making process in the way that the decision will be based on facts and not just on personal opinions and experience. The improvement and coaching Kata methods will have their strength in the implementation phase of the chosen solution as shown in Figure 2.

## 3 WHAT ARE THE BARRIERS

When implementing lean in a company, there are barriers to overcome. It is essentially the same when a company is interested in applying tools such as simulation and optimization. There is literature available on these two topics, but this section aims to identify what would be the barriers when integrating lean, simulation and optimization and implementing the approach in real-world cases:

- *Reaction to change*: while lean practitioners are used to traditional lean tools, simulation engineers are used to work on their own. Including simulation and optimization as additional tools in the lean package and including the soft principles of lean such as team work or the behavioral and systematic approach presented by the Kata methodology in the simulation and optimization process, will certainly provoke a reaction among the people involved in the process. The key will be to demonstrate by experimentation the benefits that arise from the integration.
- *Involvement of managers*: the understanding by managers of the benefits that this approach can offer is fundamental, especially when talking about including simulation and optimization as tools to evaluate and make decisions about future states within a lean process. As the managers are commonly involved in the decision making process, the rejection or misunderstanding of this approach would be one of the biggest barriers to overcome.
- *Required expertise*: simulation and optimization require a level of expertise in order to develop and run them. The advantage of most of the lean tools is that they are simple and easy to use. The ease-of-use of simulation is still presented as a need in the literature (Robinson 2005). The same applies to optimization and the analysis of the results obtained from this technique which may be perceived as difficult and abstract to understand.

- *Generation breach and reliability*: The oldest generations of lean practitioners usually have difficulties to believe in simulation´s power, sometimes even if they have a simulation model, they are used to take decisions based on experience and if their opinion is not according to what the simulation and optimization are showing, there is a tendency to disbelieve the simulation model. Education in what simulation and optimization are may help but will not be enough, so their application in different projects is necessary.
- *Losing the Gemba*: The perception of having simulation engineers sitting in their office being far away from the shop-floor and working alone, can make lean practitioners have doubts about this approach. It is crucial that simulation and optimization support and enhances the shop-floor focus required by lean (Detty and Yingling 2000). So simulation engineers will have to be involved in the shop floor and more people will have to be involved in the simulation-optimization process in order to get a rich outcome in the project.
- *Previous negative experiences*: If previous experiences with lean or simulation and optimization have not been successful, it will certainly complicate the adoption of this approach in the company. This new approach, integrating lean and SMO, may actually be the solution to the failure. For example, as presented by Anand and Kodali (2009) lots of companies lose the faith in what lean can offer them, being the main reason that the managers do not understand the future state after a lean implementation. As described in this paper, simulation and optimization can solve this problem.
- *Terminology*: the terminology used by lean, simulation and optimization is not the same. For example, in lean language the target is the objective function of optimization. The use of the same language should be agreed in order to facilitate the communication in the organization.

## 4 AN INDUSTRIAL EXAMPLE

This section addresses how a real-world lean improvement project was supported by SMO which identified the exact areas of improvements in the system to reach the desired target condition. The complex production line under study was the same one presented in Ng, Bernedixen, and Pehrsson (2014). While that article was focused on the relationship between bottleneck improvement and SMO, this paper mainly reveals the project process and results from a lean perspective.

The complex production line is an automotive component machining line that includes multiple parallel sections, portal cranes, machining centers and assembly stations which conduct multiple operations. Apart from some maintenance issues that affect the machine availabilities, tens of variants have to be processed in the line and variations in the weekly volume contribute to the high variability of the system. The company wanted to increase the production capacity of this line, which was the "bottleneck" of the entire plant. A lean improvement team was on the matter but given the size, complexity and variability of the line, it was believed to be extremely hard to locate where and what to improve, let alone the effect of performing the improvements, if only traditional VSM tool had been used. And it was obvious that not a single, but multiple improvement actions had to be made in order to achieve the targeted throughput level demanded by the management of the company. The engineers in charge decided to build a simulation model for the evaluation purpose of the current state and target condition as presented in the framework in Figure 1. The project followed the main steps of the process presented in Figure 2, starting from the problem of the poor production capacity to the implementation of the resulting improvements.

Several versions of the simulation model were developed to define the current state but the last complete model as shown in Figure 4 was built in FACTS Analyzer (Ng et al. 2011). The rapid modeling and user friendliness of FACTS Analyzer has endowed the production engineers with the possibility to build/update simulation models for their own production lines and thereby minimizing some of the barriers mentioned above. Additionally, more than 200 production engineers at the company have taken part of a production systems development course where lean concepts, basic statistics, input data analysis, DES and SMO are included in a full-week training. Although not all of them have developed the skill (interest) or are being allocated with the times to adopt simulation into their daily work, the education has endowed them with the knowledge to cooperate and understand the benefits of the integration of lean and SMO development in improvement projects.

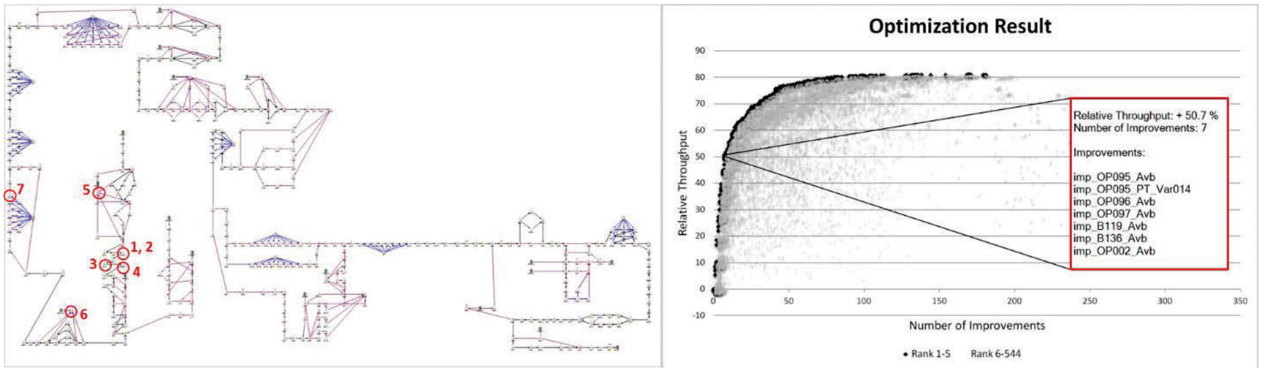


Figure 4: The simulation model and SMO results in a real-world lean improvement project.

Having finalized the simulation model, the next step included that all production and maintenance engineers proposed in kaizen workshops a set of possible improvement options, including reduced processing times (per variant where applicable), increased availabilities, and reduced mean times to repair (MTTR) defining therefore the target and target condition. Table 1 lists the number of improvement variables of each type and also the range of the improvements of that type, e.g. the processing time reduction ranges from only 0.2 % for one station to 41.8 % for another station. That summed up to 464 improvement alternatives which were represented in the optimization problem as binary Multiple Choice Set (MCS) variables, for more detail see Bernedixen and Ng (2014).

Table 1: Improvement details

| Type of improvement variable | Number of variables of this type | Range (min-max) |
|---|---|---|
| Processing time | 317 | -0.2% to -41.8% |
| Availability | 82 | +0.1% to +23.8% |
| MTTR | 65 | -5.5% to -92.1% |

The optimization results showing the optimal trade-offs between minimizing the number of improvement actions and maximizing throughput are also shown by a Pareto front in the data plot in Figure 4. The results are only presented as relative change in percent from the original state (i.e. no improvements) to maintain confidentiality. The optimal improvement actions found by the optimization can increase the system throughput by up to 80 %. Moreover, a significant improvement (about 50 %) can already be reached with only seven discrete system changes, as indicated by the data plot in Figure 4. These seven areas of improvement are labelled in the snapshot of the model and note that four of them are centered around one single production area. Following a lean alone perspective, to conclude that these are the improvements that have to be addressed for the system to be improved in that significant way, would have been extremely time costly and even then, the lean process does not guarantee that they would have been identified. The optimization results actually surprised the production engineers as they had believed that the major problematic areas that should be improved and prioritized were somewhere else. If just a lean approach had been followed, trial and error would have been performed in these other areas resulting maybe in some improvement of the system, but certainly not in the good results presented by the SMO approach. Subsequent decision making was made based on the SMO results and lean tools were later used in the implementation phase in order to carry out the above mentioned improvements. The engineering team also concluded that the optimization results greatly facilitated their discussions and cooperation as well as supported their decision making when compared with only traditional lean methods and tools that had been used. This study therefore exemplifies how SMO can significantly enhance lean and avoid being trapped in the unknown gray zone as illustrated in Figure 3. The process followed during the project (see Figure 2) can be applied to answer other real-world problems in the industry in order to benefit from this approach.

## 5 CONCLUSIONS AND FURTHER WORK

This paper has presented a novel framework where lean, simulation and optimization are combined and it has been described how each one of them benefits from this combination. Adding simulation and optimization into the lean toolbox can strengthen, besides others, some of the main drawbacks of lean such as not considering variation, lack of dynamicity and the incapability of lean standard tools of evaluating complex non-existing processes before implementation. Additionally, optimization is a tool that offers the optimal solutions to the decision makers, making the discussions about what to implement based on facts.

On the other hand, taking into account the lean principles in the simulation and optimization process will have an important impact in the way these processes are carried out. Key lean concepts such as team work, organizational learning, improvement Kata, etc. have to be included in simulation and optimization processes. And people with lean knowledge should be part of these processes, to ensure that the outcome of the simulation and optimization is aligned with the lean principles.

In a win-win combination scenario, the adoption of this framework in the companies will make the company succeed in designing and improving its processes even more than implementing lean or simulation and optimization alone. A real-world industrial example that supports this statement has been presented as well as a simplified version of a lean and SMO combined process that can be extended to other companies.

Future work will include the development of a detailed framework where lean, simulation and optimization are working to benefit each other. A handbook will also be developed where each of the stages of this framework will be explained. Pilot studies will be performed in different companies in order to validate the approach.

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