A Simulation Approach for Spare Parts Supply Chain Management

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Abstract

To be competitive, companies must constantly innovate, and having efficient and well-managed supply chains is undoubtedly an important success factor. In the case of spare parts manufacturing, supply chain management is a very complex and arduous task. Quite often, spare parts have to be produced for products that have been on the market for very long, with the need to keep a large and varied stocks to ensure supply service level. With an increasing investment in the development and applications, the Additive Manufacturing (AM) technology can yield significant benefits to spare parts manufacturing. AM allows the production of parts with a high level of customization, without the need for setups, and helps to decrease costs, inventory levels and lead time. This new reality creates numerous challenges, forcing the design reformulation of traditional supply chains, and leading to an allocation of the production of certain types of parts downstream. This paper proposes a simulation model to address the use of the 3D printing technology on the supply chain of an elevator maintenance service provider. The simulation model allows the assessment of new supply chain designs, measuring their performance, thus avoiding the need of experimenting new solutions in the real system.

Keywords
Supply Chain, Additive Manufacturing, Simulation, Decision Making.

1. Introduction

For a company with highly complex and customizable products to be competitive, its supply chain needs to be flexible enough to easily adapt to the changes of today's business environments (Von Der Gracht and Darkow, 2010, Khajavi et al., 2014). Supply chain design is, therefore, an important factor for achieving good operational performance, and it should carefully consider all the involved entities (suppliers, final customers, etc.), along with parameters to accomplish the best "utilization" of those entities (Garcia and You, 2015). In practice, the design of a supply chain should take into account quite different factors, such as the bullwhip effect (Reiner and Trcka, 2004), the transport activities, scale and complexity, and the location of the facilities, particularly relevant when the company operates at a global scale (Garcia and You, 2015, Melo et al., 2009).

The evolution of technologies, such as the case of additive manufacturing, is bringing significant changes to supply chains. This technique is used to produce three-dimensional objects (Achillas et al., 2015), and creates numerous opportunities for industry, since it is flexible and allows a high level of customization. In the spare parts supply chains, the use of additive manufacturing has an enormous potential to be explored (Khajavi et al., 2014), because it enables the production of old spare parts, not economically viable to be in stock, with low cost and production time. Moreover, this new paradigm brings production closer to the customer in the supply chain.

In the case of a company that commercializes products with a high level of customization, managing the supply chain and stock levels may be a very complicated task. This paper tackles a case study of this nature, with a company that produces elevators of many different models and performs their maintenance. Some of the elevators in which the maintenance is performed have been in operation for more than a decade, and other elevator models may need quite different spare parts for preventive or for corrective maintenance. Implementing additive manufacturing technology (in this case, 3D printing) makes it possible to produce a considerable number of these parts. In fact, this technology has significantly evolved in the manufacturing industry during the last years and is expected to go on evolving (Columbus, 2017). Applying it to the case study led to a considerable reduction in the lead time, while maintaining the stock levels low or non-existing for various spare parts.

This paper proposes a generic simulation model (built using the Simio simulation software) to develop and assess different supply chain configurations with the 3D printing technology. This technology is used to produce some plastic spare parts for the elevators maintenance. The model is capable of simulating the installation of the 3D printers in any of the internal facilities of the company, and allows changing the supply chain design between runs of the model.

The paper is organized as follows. Section 2 presents a brief literature survey on supply chains, additive manufacturing and simulation. Section 3 details the case study. Section 4 describes the proposed solution, that incorporates a simulation model for spare parts supply chain management. Section 5 shows how the proposed solution was validated. Finally, Section 6 presents some concluding remarks.

2. Literature Review

2.1 Supply chain management

Beamon (1998) described a supply chain as “an integrated process wherein a number of various business entities (i.e., suppliers, manufacturers, distributors, and retailers) work together in an effort to: acquire raw materials, convert these raw materials into specified final products, and deliver these final products to retailers”. The scale and complexity can grow considerably for global supply chains (Garcia and You, 2015).

For a company to achieve a better understanding of the market and a high customer satisfaction, a good performance of the supply chain is clearly required. A supply chain that responds with short lead times and can adapt to the demand changes is crucial for the success and survival of a company, because of the increasing competitiveness in the global market and of the search for reducing the inventory level and costs (You and Grossmann, 2008). The characteristics that distinguish a good chain are: (i) how it converts inputs into outputs; (ii) how the resources are used; and (iii) how it responds to the client’s requests (Khajavi et al., 2014). Supply chain management is therefore a crucial function in modern companies (Eskandarpour et al., 2015).

Supply chain management is “the process of planning, implementing and controlling the operations of the supply chain in an efficient way” (Melo et al., 2009). This process involves managing the work-in-progress inventory, the finished goods, and the raw materials, as well as the routings, distribution, inventory, and production, to better serve the company (Melo et al., 2009).

In the particular case of spare parts, supply chain management is expected to reduce the operations costs and to maintain customer’s satisfaction at a high level. However, many challenges need to be overcome, as it is the case when the company launches a new product in the market and cannot forecast its demand. This type of supply chain is hard to manage because guaranteeing the customer’s satisfaction could imply a significant increase in the stock levels for both old and new products (Khajavi et al., 2014).

Moreover, one of the main objectives of supply chain logistics is to choose the best location for the facilities of a network (Yun et al., 2015). Given the continuous industry growth, this area is becoming more complex and dynamic and, in the future, will face numerous challenges, but will also create many interesting opportunities (Von Der Gracht and Darkow, 2010). In closed-loop supply chains, logistic activities are even more complex, because of the need to consider where to repair and disassemble the products (Amin and Baki, 2017). The design of the supply chain becomes, therefore, of a considerable importance, since it has a large influence on the system’s performance (Mousazadeh et al., 2015). Since a supply chain is, in general, created to last many years, its design may be a rather complex task, but it has a long-term impact on the system (Salehi Sadghiani et al., 2015). It determines the size and location of the facilities over the various levels of the supply chain, as well as the physical flows along the chain (Eskandarpour et al., 2015). To achieve a good design, it is necessary to anticipate decisions about: (i) production, (ii) distribution, (iii) storage, (iv) transport, (v) demand, (vi) revenues and (vii) service levels (Salehi Sadghiani et al., 2015).

Based on a comprehensive literature survey on supply chain performance measures, Beamon (1998) defined a series of Key Performance Indicators (KPIs) to measure the performance of a supply chain and to compare it with alternative designs. The author divides those measures in two categories: *qualitative* and *quantitative*. Some of the qualitative KPIs are: (i) customer’s satisfaction; (ii) supply chain flexibility; and (iii) suppliers performance, whilst examples of quantitative KPI’s, are: (i) cost minimization; (ii) sales and profit maximization; (iii) inventory investment minimization; (iv) lead time minimization; and (v) in time orders maximization.

2.2 Additive manufacturing

In additive manufacturing products are manufactured with the aid of a design software. Slim layers of the raw material are produced forming a three-dimensional (3D) model created by the software application (Achillas et al., 2015). This technology only needs a raw material and 3D models of the products as inputs, unlike traditional production methods that would require setups to start producing and some tools to execute tasks (Pour et al., 2016).

This type of technology is having a large impact in industry, since it allows manufacturing products with a high level of customization and reducing production costs, lead times and the complexity of the supply chain. Currently, this production method is largely beneficial for low volume production lots (Bogers et al., 2016). Another advantage of additive manufacturing is the possibility of easily changing the product design, thus offering great flexibility, not only for the manufacturer, but also for the client. Studies have been made to apply this technology in sectors such as the aerospace industry (Pour et al., 2016) or the food industry (Sun et al., 2015), or in other areas such as medicine (Murphy and Atala, 2014). Moreover, the technology was applied to a services company that outsources another company to manufacture products using 3D printing (Rogers et al., 2016).

Additive manufacturing can significantly change the spare parts industry in the future, due to cost and production time reductions and to an increase of supply chain robustness. These benefits can deeply change operations in areas such as logistics or stock management (Khajavi et al., 2014). In spite of the impressive recent evolution, there are still many opportunities to improve this technology and apply it to many new industrial sectors (Attaran, 2017).

2.3 Systems simulation

Simulation techniques and tools aim at imitating a process or a real-world system in a computer system (Banks et al., 2001). To simulate something, first it is necessary to develop a model that represents the main characteristics or behaviors of a certain physical or abstract system. While the model represents the system itself, the simulation represents the operations in the system as a function of time. Simulation can also be used to study the functionalities of a natural or human system, and to demonstrate the effects of alternative actions or decisions in possibly different contexts. One of the main strengths of simulation is that it avoids experimenting alternative solutions in the actual system, which might be dangerous, very costly or not even possible (Sokolowski and Banks, 2009).

Manufacturing systems and supply chains are important application areas of simulation, as this technique can be a very valuable tool to evaluate the effects investing in physical equipment and facilities such as factories, warehouses or distribution centers. Simulation can be used to predict the performance of a planned system and to compare alternative solutions, in a multi-criteria perspective, as a way to design better systems (Benedettini and Tjahjono, 2009). Another important goal of simulation in manufacturing is to quantify system performance. Banks et al. (2009) describe the most common performance measures for simulation of manufacturing systems: (i) average demand or peak demand; (ii) system cycle time; (iii) use of resources, (iv) machines and labor; (v) bottlenecks; (vi) queues and delays; (vii) required stocks; (viii) required labor; (ix) effectiveness of planning systems; and (x) effectiveness of control systems.

Banks (2000) has also highlighted the main strength and weaknesses of simulation. Advantages include: (i) testing changes in a system or exploring new scenarios without compromising resources; (ii) accelerating or decelerating phenomena to be studied, by manipulating the simulation time; (iii) finding new problems and getting a better understanding of system variables and their interactions; and (iv) answering “what if” questions when designing new systems or redesigning existing ones. On the other hand, some disadvantages of simulation are: (i) it requires specialized training; (ii) results can be hard to analyze; and (iii) modelling and analyzing simulation models can be very time consuming.

There are various types of simulation such as "system dynamics" (Tako and Robinson, 2012) or "agent-based simulation" (Siebers et al., 2010) but this work is based on the so-called "discrete event simulation" (Tako and Robinson, 2012). This is one of the most common simulation methods and is largely utilized to simulate operational and tactical problems. The models are used to better understand the behavior and performance of a system in different situations. This type of simulation is "process oriented" as a way to make a detailed system representation, with the different entities being individually simulated. Discrete event simulation can be used to add variability and uncertainty to the models that are usually stochastic (and probability distributions are used) (Tako and Robinson, 2012, Siebers et al., 2010).

Tako and Robinson (2012) have studied the utilization of simulation as decision support systems in logistics and in supply chain management. The objective of this study was to check which simulation technique was the most utilized in these situations, and they have shown that discrete event simulation was in fact the natural choice in many situations.

Simulation allows to evaluate alternative supply chain designs and to assess the impact of lead times and quality levels in costs (Persson and Olhager, 2002), being highly useful in supply chain management (Tako and Robinson, 2012). Persson and Olhager (2002) have created a discrete event simulation model to test different designs of a supply chain, and they have used a "nine activities methodology" to validate the simulation. This validation methodology was used in the work described in this paper. To study an automotive supply chain, Pierreval et al., 2007 used simulation models obtaining quite satisfactory results and highlighting undesired behaviors of the system.

Bottani and Montanari (2010) have developed a discrete event simulation model to analyze the "bullwhip effect" and the total costs of various supply chain designs, in the case of fast selling products. Longo and Mirabelli (2008) proposed a discrete event simulation model for supporting supply chain management. The model was built using commercial simulation software with an object-oriented approach, and through the simulation interface, simulation scenarios can be changed, and obtained results exported to Excel sheets.

3. Case Study

The case study presented in this paper was designed around a Brazilian company that provides elevator maintenance services. One of the company's goals is to use additive manufacturing (3D printers) to produce spare parts used in the maintenance of elevators. The company wants to produce spare parts using 3D printers, and intends to install additive manufacturing cells on some of their facilities scattered over Brazil. This will hopefully lead to improving the maintenance services, and reducing stock levels, lead times and costs. However, these changes will create numerous challenges in terms of the supply chain, as presented above. The internal facilities chose to host these additive manufacturing cells will be able to supply spare parts to other internal facilities, thus creating another level of complexity.

Therefore, the company needs tools to support decision-making and to evaluate the impact of the changes made in the supply chain, without compromising the operation of the real system. This paper proposes a simulation model capable of representing the whole logic and behavior of an adaptive supply chain, testing different designs and measuring their performance. The next section presents the methodology used in this work and the characteristics and requirements of the company's supply chain simulation model.

4. Proposed Solution

4.1 Methodology

The methodology used (Figure 1) is similar to the one presented by Persson and Olhager (2002) and is composed of five activities.

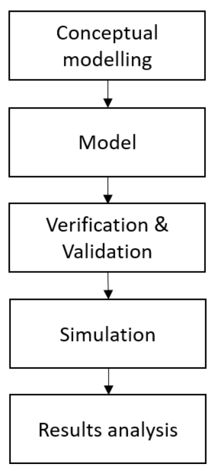

Figure 1. The methodology used in the development of the simulation model

The first activity is the *conceptual modeling*. This activity defines and validates the case study requirements of the simulation model, as a way to achieve an adequately realistic and coherent model. In the *model* activity, the Simio simulation software is used to create a simulation model with all the current and future logic and characteristics required by the company's supply chain. The *verification and validation* activity tests and validates the model. In the next activity, *simulation*, the model is executed using a given supply chain configuration and demand, in order to assess its performance. In the final activity, *results analysis*, the simulation results are analyzed to verify, validate and measure the impact of the supply chain configuration under study.

4.2 Supply Chain Modelling

To simulate the company's supply chain, in the first activity (conceptual modeling), several entities were identified:

i) Supply chain centers – including internal facilities and external suppliers of the company;
ii) Group of customers – a group of clients with elevators installed, in each area of operations in Brazil;
iii) Transport – representing a physical resource, and the time, a given order takes to reach its objective; and
iv) Orders – purchase/production orders in the supply chain (as explained below).

Moreover, in this activity the main requirements of the simulation model are raised, including:

i) capacity of simulating the existence of additive manufacturing cells in any internal facility of the company;
ii) changing the number of 3D printers of each cell in a new simulation run;
iii) a model able to change the supply chain configuration (i.e. changing the supplier of each internal facility, for each spare part);
iv) reading the inputs (as listed above) from an external source; and
v) measuring the lead time and costs of the supply chain.

To be able to cope with all the requirements identified, in the second activity (model activity) a set of classes was created that gathers the whole logic and behavior of the main entities of the supply chain. It is, therefore, quite easy to add or remove supply chain centers and clients.

The simulation model has three different classes. The first class, *Orders*, represents the types of orders:

i) *EntOrders* – an order from a client to an internal facility;
ii) *EntInternalOrders* – an order from an internal facility to another; and
iii) *EntSupplierOrders* – an order from an internal facility to an external supplier.

Each order carries information about the products required, the quantity, the destination and, as explained above, the time to reach the destinations (a static value or a probability distribution). These input parameters are read from an Excel file.

The second class is the *Final Customers* that represents the groups of clients of an area, and it creates the orders from that area, following probability distributions of the demand. The demand values are a changeable input of the simulation model. The lead time of each area is measured.

The last class, the *Supply Chain Centers*, simulates both internal facilities and external suppliers of the company, as well as their behavior. The centers manufacturing strategy can be Make-To-Order or Make-To-Stock, with a periodic revision of the stock levels, with the time between revisions possibly being different for each center. For both types of supply chain centers, their input parameters are transferred to the simulation model from an Excel file. For each center and products, it is possible to define: (i) the supplier; (ii) initial inventory level; (iii) reorder level; (iv) quantity to get filled; (v) production time; (vi) lot size; (vii) unitary cost; and (viii) all transportation times and costs. Also, when a center represents an internal facility, it is possible to define the number of 3D printers installed, and their production capacities.

To measure the individual performance of the centers and the whole performance of the supply chain, some KPIs were defined, namely: (i) Average Service Level; (ii) Average Production Time; (iii) Average Lead Time; (iv) Average Inventory Level; and (v) Average Number of Stock outs. Some costs are measured as well: (i) the total cost of a center and supply chain; (ii) the inventory costs, (iii) the stock out costs; and (iv) the production and supplying costs.

4.3 Case Study Simulation Model

The geographic zone covered by the case study is presented in Figure 2. and the simulation model developed for its supply-chain has 32 internal facilities and clients (map points) and no external suppliers. These are the potential locations for installation of additive manufacturing cells in the future.

With this version of the model, it is possible to test and assess a large number of supply chain designs, by changing the input parameters on the input file. The input file used in this version of the model is an Excel file. Moreover, the time frame of the simulation run could be changed between any two runs.

The model could be fed with forecasted demand data, to estimate the performance of the supply chain with additive manufacturing cells or with no cells. External suppliers were also added. In this way, the performance of the supply chain without in the future could be estimated, and different scenarios compared.

Figure 2. Case study simulation model

The results produced can be viewed using different reports or dashboards. The dashboards were created to better analyse the KPIs and cost breakdown, and were designed with bars, and pie and line charts. The charts have labels, that indicate the value and the source. It is possible to filter the contents by supply chain centre, product, cost and/or KPI. The dashboard on inventory and service levels presents these KPIs in line charts, showing their evolution over time.

5. Validation results

An experimental case was defined in the third activity (verification and validation activity) to check and validate the classes developed in the second activity (model) and ensure the case study simulation model would perform correctly. For this purpose, a fictional instance was developed, with a supply chain composed of 3 final customers, 3 internal facilities, 2 external suppliers and 5 spare parts (some are produced using additive manufacturing, and others are supplied by external suppliers). Both internal facilities and external suppliers operate on a make-to-stock strategy.

The simulation model of this illustrative supply chain was run, thus generating results (simulation activity) to be compared with the theoretical expected results (result analysis). The Table 1 shows both a theoretical and a simulation cost breakdown, while Table 2 shows the average lead time and average service level .

Table 1. Illustrative supply chain cost breakdown

Cost	Theoretical	Simulation
Fixed	€ 66.000,00	€ 66.000,00
Production and supplying	€ 279.679,50	€ 271.527,06
Inventory	€ 612,40	€ 947,88
Stockouts	€ 0,00	€ 10.600,00
Total cost	**€ 346.291,90**	**€ 349.074,94**

Table 2. Some KPIs of the illustrative supply chain

	Theoretical	Simulation
Average Lead Time	4h	4.5h
Average Service Level	1	0.98

As shown in Table 1 and Table 2, the theoretical and the simulation results are slightly different. This difference reflects the stochastic component of the simulation. The simulation results have a more realistic behaviour, as the model takes into account some unexpected events, such as stock outs. From the theoretical results, this could not be predicted as these results were generated using static input parameters, while the simulation used probability distributions to simulate the demand for spare parts and transportation times.

The differences between the theoretical and simulation results are small, and the logic and the behaviour of the experimental case simulation model worked as expected. Considering the experimental case results and given that the classes developed have been validated, it is possible to build new simulation models for supply chain designs, as expected.

6. Conclusion

The main objective of this work was to develop a simulation model capable of measuring the impact of using the additive manufacturing technology (3D printing) in a supply chain. After defining the main features and requirements of the system, classes representing the supply chain entities were created to model their logic and behaviour. Then, a simulation model of the company's supply chain was built. A series of dashboards was produced to visualize the KPIs and cost breakdown of the system, and to support the analysis of the results generated by the model.

The developed model allows the end user to test the installation of additive manufacturing cells (with different production capacities) in any of the internal facilities of the simulated supply chain, and measures the impact of these changes with KPIs and cost breakdown dashboards when the model runs. Since the classes represent different entities of the supply chain, they provide the model with some flexibility to add or remove entities. With this feature, the model is able not only to test the impact of additive manufacturing, but also the impact of removing or adding a new internal facility or external supplier, and/or products to the supply chain.

In the work described in this paper, the simulation model was applied for a specific case study, but the model is more general, encompassing other characteristics that can be very interesting in practice. The model was tested and validated using an illustrative instance of a supply chain that was designed specifically for that purpose. Nevertheless, this model can be applied not only to other supply chains that want to evaluate the use of additive manufacturing in their chains, but also to supply chains of other industrial sectors that want to try some changes in their processes, without compromising the real systems. The model developed in this work could also become a powerful to support the supply chain managers in decision making processes and in getting insights about the cost breakdown and KPIs of their company's supply chains.

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Biographies

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