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Exploring Fragility and Antifragility under Uncertainty through Discrete Event Simulation

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Abstract: The behavior of systems under uncertainty can be described on a spectrum ranging from fragility, where losses are disproportionate to variations, through resilience, where losses and gains are proportional to changes, to antifragility, when gains disproportionately exceed volatility. In this study, Arena™ discrete event simulation software was used to compare the behavior of key variables under different levels of volatility in two production models: mass production and just-in-time, applied to a bicycle factory that uses three different types of metal. The results indicate that, when subjected to the same exogenous variables, the models react differently to different types of volatility, displaying, in different scenarios, characteristics of fragility, resilience or antifragility.

Keywords: discrete simulation, lean production, mass production, fragility, uncertainty.

Análise de fragilidade e antifragilidade sob incerteza por meio da simulação de eventos discretos

Resumo: O comportamento de sistemas sob incerteza pode ser descrito em um espectro que vai da fragilidade, onde as perdas são desproporcionais às variações, passando pela resiliência, em que perdas e ganhos são proporcionais às mudanças, até a antifragilidade, quando os ganhos superam desproporcionalmente a volatilidade. Neste estudo, utilizou-se o software de simulação de eventos discretos Arena™ para comparar o comportamento de variáveis-chave sob diferentes níveis de volatilidade em dois modelos produtivos: produção em massa e just-in-time, aplicados a uma fábrica de bicicletas que utiliza três tipos distintos de metal. Os resultados indicam que, quando submetidos às mesmas variáveis exógenas, os modelos reagem de maneira distinta a diferentes tipos de volatilidade, exibindo, em cenários variados, características de fragilidade, resiliência ou antifragilidade.

Palavras-chave: simulação discreta, produção lean, produção em massa, fragilidade, incerteza.

1. Introduction

Rooted in the success achieved by the Japanese automotive industry in the 1980s, the lean production methodology has become the dominant paradigm in the literature and in the practices of modern industries (HOLWEG, 2007), as opposed to the previous dominant methodology of mass manufacturing, which, despite tracing its origins to the

Industrial Revolution, had its pinnacle in the practices of the Ford Motor Company, inspired by Taylor's principles of scientific management (CHANNELL, 2018). In this paper, these methodologies were identified as lean and mass, respectively.

The trade-offs involved in adopting one or the other production methodology are widely discussed in the literature, with the mass methodology known for its greater economies of scale, while lean has lower operating costs (GYENGE; SZILÁGYI; KOZMA, 2015). The risks involved in each choice, however, were revisited after the shock suffered by global supply chains following the SARS-CoV-2 pandemic in 2020, when it was realized that both methodologies were impacted differently, with various consequences for organizations (BIANCO et al., 2023).

In this context, one way of assessing the impact of volatility on a system is the approach presented by Taleb (2012), where systems are classified as fragile, whose negative response to shocks grows exponentially, resilient, affected by volatility in a linear way, or antifragile, which benefit exponentially from the same volatility. This difference in response can have vital consequences for a company, indicating either bankruptcy or growth.

For this work, it was decided to replicate a case study presented by Womack and Jones (2003), about the change of production methodology in a bicycle factory, from mass to lean, through discrete event simulation, and then evaluate the impact of shocks in different scenarios on determined variables, seeking an indication of which production methodology can be considered the most fragile, robust or anti-fragile.

2. Theoretical framework

2.1 Production methodologies

The mass approach is characterized by the mass production of homogeneous products, with a production schedule that is not directly linked to current demand and is therefore geared towards inventory creation. This methodology benefits from economies of scale, keeping the cost of each item produced at the lowest possible level, but is subject to higher inventory carrying costs and takes longer to adapt to sudden changes in supply and demand conditions (MITAL, 2014).

The lean approach, according to Womack and Jones (2003), is characterized primarily by just-in-time order management, where production is linked to each individual order and all raw materials arrive at the production plant only when they are needed for production, thus reducing inventory levels as much as possible. Industries that adopt this methodology depend on high coordination with their suppliers and total integration between the sales and production teams, and don't benefit from the same gains in scale as those that produce in the mass format, but, on the other hand, have lower inventory carrying costs and are quicker to adapt to sudden changes.

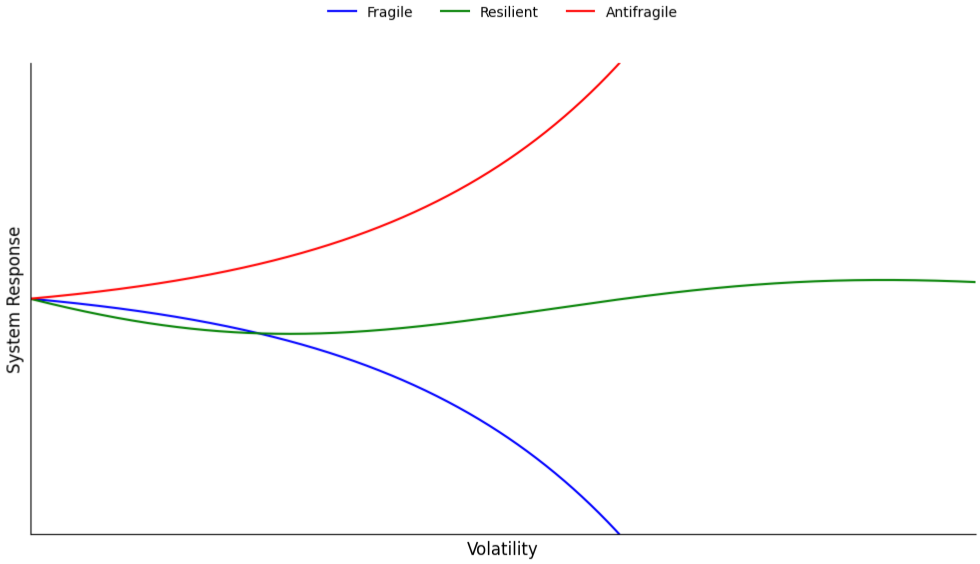
2.2 Fragility, resilience and antifragility

The definition of fragile, antifragile and resilient systems is given by Taleb (2012):

> Some things benefit from shocks; they thrive and grow when exposed to volatility, randomness, disorder, and stressors and love adventure, risk, and uncertainty. Yet, in spite of the ubiquity of the phenomenon, there is no word for the exact opposite of fragile. Let us call it antifragile. Antifragility is beyond resilience or robustness. The resilient resists shocks and stays the same; the antifragile gets better. (TALEB, 2012)

By contrast, fragile companies are those that are not only damaged by shocks, but are also subject to catastrophic losses, i.e. they are worse off. Graphically, the fragile has a concave response to volatility, while the anti-fragile has a convex response, as shown in Figure 1:

Figure 1 – Behavior of systems under volatility



Source: Author, based on Taleb et al. (2012).

According to Taleb et al. (2012), the behavior of the system's response is decisive in distinguishing fragile/antifragile systems from resilient ones and those that are simply exposed to volatility: fragile/antifragile systems show exponential behavior, i.e. disproportionate to the variation in volatility. The other systems show linear behavior, proportional to the magnitude of the shock suffered.

In systems where the response can be measured in a cumulative way, such as profits in a company, for example, fragile systems are said to have limited gains and unlimited losses, while antifragile systems have limited losses and unlimited gains (TALEB, 2012).

2.3 Discrete event simulation

As argued by Iwańczyk (2015), discrete event simulators are widely used to simulate production processes and consist of entities moving between processes and queues, subject to limited resource and other restrictions determined by the user. One of the advantages of these simulators is the ability to insert stochastic processes into the production process, which makes it possible to design systems exposed to non-constant/linear scenarios.

Among the discrete event simulator softwares is Arena™ Simulation Software, developed by Rockwell Automation. This software was chosen for this work because it is easy to adapt industrial process flowcharts to its interface.

3. Methodology

The mass and lean flowcharts of the case study presented by Womack and Jones (2003) and replicated in Figure 2, referring to the manufacture of steel, aluminum and titanium bicycles, were replicated in the form of models in the Arena™ software, with some small adjustments and the creation of attributes, entities and variables that enable the execution of stochastic events, as shown in Table 1 of the appendix.

Figure 2 – Production plant in the mass and lean models

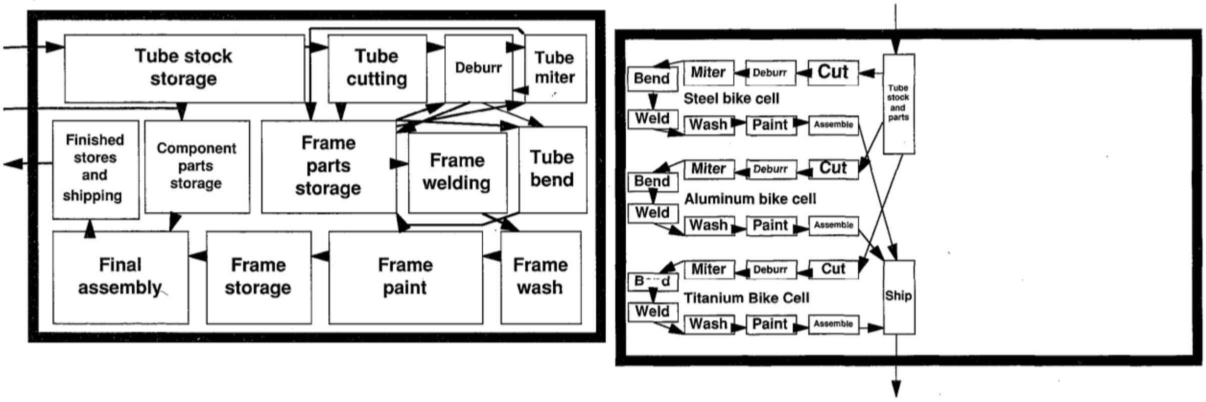


FIGURE 3.1: BICYCLE PLANT LAYOUT AND FLOW

FIGURE 3.2: LEAN BICYCLE PLANT LAYOUT AND FLOW

Source: WOMACK AND JONES, 2003, p. 57 and 62.

The mass model presents a raw material purchase and production schedule based on the demand observed over the last n days, with n being an adjustable variable in the model. Because of this approach, it is necessary to keep a minimum stock of finished products to ensure that orders are met before the start of each new production cycle. In this model, each production station consists of one machine with one operator and processes all types of metal materials on a first-come, first-served basis. Defect inspection takes place only once at the end of the entire process, and defective bikes are disassembled and reinserted at the start of the production line.

By its part, the lean model shows no stock, and the raw material purchase and production schedule is determined by customer orders, i.e. as soon as an order is received, the raw material is purchased, and production begins for that unit. Its production stations are dedicated to one type of material, so this model has three times more installed capital and thus requires more manpower in the form of operators. In addition, defect inspection is carried out in each production module, allowing defects to be corrected immediately at the station itself.

For the purposes of this study, no depreciation or labor costs were considered, so the difference in capital and labor intensity between the models is disregarded. It is assumed that these considerations will be weighed up when deciding whether to switch from one model to another, and such a change would only be made if the benefits expected from it are greater than the increase in capital and labor costs.

The average working time at each production station and the probability of defects were estimated based on the information presented by Nugroho, Marwanto and Hasibuan (2017), Kholik, Ngatilah and Purnamawaty (2020), Shen et al. (2009) and McCabe and Ostraff (2000). In both models, demand was set to ensure that in one day the quantity demanded is, on average, equal to the maximum quantity that could be produced in that time.

The values of the variables of interest were obtained after running 10 simulations for each scenario in each model, with each lasting 730 days with 8 hours. All the scenarios can be seen in Table 2 in the appendix and are made up of four degrees of the factors that impact the characteristics of the systems, assuming higher and lower values than those of the base scenario, except in cases where lower values would not make sense.

When developing the models, it was ensured that, for comparison purposes, the values of the exogenous variables were equivalent in the base scenario of the two models, and the performance of each of the models under this base scenario can be seen in Table 1:

Table 1 - Value of variables in the base scenario

Variable	Mass Model	Lean Model
Total Orders	16035	16033
Orders Fulfilled	15908	16031
Wait List	127	2
Initial Stock	154	-
Finished Bike	15908	16031
Total_Revenue	8,950,970	9,259,300
Total_Costs	8,371,120	8,406,990
Total_Profit	579,850	852,310
Average_Resource_Utilization	19%	6%

Source: Author.

The results were analyzed using box plots representing the observed values, and simple line graphs, which are quadratic extrapolations. Fragility was verified by evaluating the limitations of losses and gains and by the quadratic extrapolation, since, as can be seen in Figure 1, the behavior of systems under volatility can be inferred through the convexity of the response (TALEB et al., 2012).

Finally, key variables were chosen to assess the impact of volatility and were treated as dependent variables: profit, number of unfulfilled orders (wait list) and average resource utilization. The independent variables were raw material freight time, prices, costs, demand and, in the case of the mass model, the demand forecasting factor. For some independent variables such as costs and prices, symmetrical variations were considered when the variables of all products/materials vary in the same proportion at the same time, and asymmetrical when they change one at a time.

Each value on the horizontal axis, representing a scenario degree, is the value by which the independent variable has been multiplied. Thus, the difference between a degree with a value of 1 and one with a value of 1.5 represents a 50% increase in the value of the independent variable. In the case of line graphs the same pattern is maintained, but they also show extrapolated, unobserved values.

4. Results and discussions

4.1 Profit

In both models the relationship between profit and raw material freight time was almost linear, as can be seen in figures 1 and 2 of the appendix, suggesting that freight time affects results proportionally. However, this linearity implies that in scenarios where freight time increases, profits fall moderately, without showing signs of severe fragility. The lean model, showing less profit variation in response to freight, shows greater resilience in this regard, while the mass model is more susceptible to slight fluctuations.

As for the variation in costs and prices, the two models are similar: profit has an inverse linear relationship with costs, and a direct linear relationship with symmetrical price changes, as shown in images 3 and 4 of the appendix. Under asymmetric price changes, the two models show a concave relationship, with profit increasing up to a certain point and then decreasing, following the consumption behavior of a common good in microeconomic literature (VARIAN, 2016), as shown in figures 5 and 6 of the appendix.

Another observation is that any increase in costs or decrease in prices, symmetrical or asymmetrical, leads both systems to losses, thus indicating fragility in these factors: the fall in costs is limited to 100%, while the increase is potentially unlimited, and, as much as the increase in prices is also virtually unlimited, any fall in prices is already capable of removing the profitability of the factories.

When the level of demand varied, the two systems showed a positive relationship in terms of profit: according to figures 7 and 8 of the appendix, even when demand fell there was no loss, and profit increased more than proportionally. Even though the extrapolation is almost linear, the slight convexity and the combination of limited losses with unlimited gains indicate antifragility in this regard for both systems, showing that their production arrangements can absorb extreme increases in demand, especially when you consider that even the most extreme drops in demand did not lead the systems to losses.

Finally, the mass model proved to be fragile in terms of the forecasting factor, as shown in figure 9 of the appendix. The highest profits are made when the same quantity is produced in one day as was demanded the previous day, and losses are incurred when production is consistent with the previous 30 or more days.

4.2 Wait list

Regarding the wait list, both models showed positive relationships in the face of changes in freight times, both symmetrical and asymmetrical, with almost linear behavior, as shown in figures 10 and 11of the appendix. For that, both showed resilience.

Symmetrical changes in prices, as well as asymmetrical and symmetrical changes in costs had no impact on the wait list for any of the models. Asymmetric price changes, however, had different effects on the models, with the mass model showing fragility and the lean model, resilience.

The fragility of the mass model in relation to asymmetric price changes can be seen in figure 12 of the appendix. Although the wait list falls as the price increases, this fall does not represent an increase in efficiency, but rather a reduction in demand. The productive arrangement of the lean model, on the other hand, is not too impacted by the change in prices of the final products, as exemplified in figure 13 of the appendix.

As for changes in demand, figures 14 and 15 of the appendix show that in the mass model these are strongly and positively related to the waiting list, growing rapidly, while in the lean model the waiting list is maintained with few changes, and tends to reduce under higher levels of demand. This result shows the absorption capacity of the two production arrangements, with lean proving to be more efficient under higher demand, being antifragile in this respect, while mass is fragile.

When varying the forecasting factor, the mass model showed a concave behavior, as shown in figure 16 of the appendix, indicating a possible antifragility: the lowest waiting list levels are found in short-term forecasts (up to a week), or in long-term forecasts (over a month and a half). This behavior indicates that the best strategies would be to follow demand closely or to have a higher levels of raw material stock.

4.3 Average use of resources

The systems behaved differently when faced with variations in freight times: in the mass model, utilization fell as freight times became longer, while in the lean model the variation was almost zero. None of these, however, can be classified as fragility or antifragility, since they may be a consequence of the low baseline resource utilization. These behaviors can be seen in figures 17 and 18 of the appendix.

There was no reaction from the systems to symmetrical changes in prices and costs, or to asymmetrical changes in costs. Regarding asymmetric price changes, both systems showed a convex relationship with the cheapest and most expensive products, but a concave relationship with the product with an intermediate price (figures 19 to 22 of the appendix). Thus, both are fragile in relation to one of the products, since peak use is capped.

Faced with uncertainty in demand, both proved resilient, since the relationship is positive and almost linear, as shown in figures 23 and 24 of the appendix. Small levels of utilization allow for an increase up to high levels of demand, potentially being a kind of antifragility, but in extreme cases, this could potentially lead to overutilization.

Finally, there is a possible antifragility in relation to the forecasting factor in the mass model. According to figure 25 of the appendix, the relationship is convex, and the lowest level of utilization is limited to forecasts of between 17 and 30 days. Before and after this region utilization is higher, which is positive under low levels of utilization predominate.

4.4 Summary of observations

On the spectrum of fragility, resilience and antifragility, the results can be summarized in Tables 2 and 3:

Table 2 - Results found in the mass model

Variable	Freight time	Symmetrical costs	Non-symmetrical costs	Symmetrical prices	Non-symmetrical prices	Demand	Forecasting factor
Profit	Resilient	Fragile	Fragile	Fragile	Resilient	Antifragile	Fragile
Wait list	Resilient	-	-	-	Fragile	Fragile	Antifragile
Resource utilization	Resilient	-	-	-	Resilient/fragile	Resilient	Antifragile

Source: Author.

Table 3 - Results found in the lean model

Variable	Freight time	Symmetrical costs	Non-symmetrical costs	Symmetrical prices	Non-symmetrical prices	Demand
Profit	Resilient	Fragile	Fragile	Fragile	Resilient	Antifragile
Wait list	Resilient	-	-	-	Resilient	Antifragile
Resource utilization	Resilient	-	-	-	Resilient/fragile	Resilient

Source: Author.

5. Final considerations

In the base scenario, the factory under lean production proved to be more agile in delivering orders, more profitable and with negligible inventory costs, at the cost of greater resource idleness and capital costs three times higher than the factory under the mass regime.

For the profit levels under uncertainty, the two models are almost equivalent, which suggests the alternative interpretation that maintaining profit levels is much more related to each player's market position: their bargaining power with suppliers and the level of competitiveness in their final goods market has much more influence on the difference between revenue and cost than their specific production arrangement.

The second evaluated factor, the wait list, represents a structural aspect of the production plant, since both models are subject to the same exogenous variables. As a result, the positions on the fragility spectrum represent essential characteristics of each of the models: lean is more responsive to variations coming from the customer side (prices and the overall level of demand), but is vulnerable to disturbances in the relationship with suppliers. Mass, on the other hand, is slower to react to changes on the customer's side, but the fact that it works with stocks allows it to recover more quickly when there are problems with the supply of raw materials.

As another structural aspect, the use of factory resources was also evaluated, considering that a factory aims at minimizing the idleness of these resources, to dilute its fixed costs. Both models proved to be on the border between resilience and fragility, with the mass model having an anti-fragile element when it manages to optimize its demand forecasting factor. As it is a structural factor, these results may be related to the low resource utilization seen in the base scenario, with the two production plant models described in Womack and Jones (2003) being subject to utilization gains after optimization exercises.

Although the results do not allow us to definitively determine which model is more advantageous, the lean model has shown greater agility in adapting to demand-related scenarios, such as price and demand, while the mass model may be more suitable in situations of uncertainty in supply, and therefore its suitability is dependent on the nature of the crisis at hand, as well as the maturity level of the specific productive plant. Future studies could deepen this analysis by including factors such as depreciation and labor costs, as well as optimized production lines and more complex simulation parameters.

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APPENDIX

So as not to hinder the overall structure of the paper, all the graphs and tables pertinent to this work can be downloaded via this link. Additionally, the discrete event simulator files for both production models can be downloaded via this link.