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The complexity of new products: a dynamic model for productivity loss analysis within productive systems

Complexidade de novos produtos: um modelo dinâmico para análise da perda de produtividade em sistemas produtivos

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Abstract: Globalization has been constantly changing the consumer market characteristics in which companies are inserted, as well as their clients' necessities. Thus, to maintain competitiveness in this market, companies need to include certain features in their products which lead to an increase in the complexity of these products. These complexities may cause unwanted effects in manufacturing productivity. Knowing this, a dynamic simulation model was developed to verify the effects that product complexity may have on system productivity. For this, bibliographic research on complexity and product complexity has been done to identify not only the elements which characterize them but also the effects they may cause in manufacturing. Through simulations, it is concluded that increments in product complexity generate a 50% productivity loss, and if the line has restrictions in its capacity, these losses are more than 60%. Ultimately, previous analysis of the changes product complexity may cause in the process is an effective tool to reduce productivity loss, which is evidence that efficient management of complexity is necessary for the processes of product development.

Keywords: Complexity; Product complexity; Productivity.

Resumo: *A globalização vem mudando constantemente as características do mercado consumidor no qual as empresas estão inseridas, bem como as necessidades de seus clientes. Deste modo, para se manterem competitivas dentro desse mercado, as empresas necessitam inserir em seus produtos determinadas características que acabam culminando com o aumento da complexidade deles. Tais complexidades podem gerar efeitos não desejados na produtividade da manufatura. De posse disto, um modelo de simulação dinâmica foi desenvolvido para verificar os efeitos que a complexidade de produtos pode causar na produtividade dos sistemas. Para isto, foi realizada uma pesquisa bibliográfica sobre a complexidade e a complexidade de produtos, identificando, assim, tanto os elementos que as caracterizam como os efeitos que podem gerar na manufatura. Por meio de simulações, conclui-se que incrementos na complexidade dos produtos geram queda de 50% na produtividade e se a linha possuir restrições em sua capacidade, tais perdas ultrapassarão a marca dos 60%. Por fim, observa-se que uma análise prévia das alterações que o aumento da complexidade pode gerar no processo é uma ferramenta eficaz para reduzir perdas na produtividade, demonstrando, assim, que uma gestão eficiente da complexidade se faz necessária nos processos de desenvolvimento de produtos.*

Palavras-chave: *Complexidade; Complexidade de produtos; Produtividade.*

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1 Introduction

Globalization and technological progress have been making the current market scenario, in which organizations are inserted, more challenging. Along with these factors, there is also the increase in clients' level of requirement, which is a result of higher amounts of available information as well as a greater number of possibilities of products offered (Gottfredson & Aspinall, 2005; Wang, 2010). These trends have forced organizations to develop differentiated products and introduce them into the market in the quickest possible way (Wang, 2010; Wang et al., 2011; Perona & Miragliotta, 2004). Thus, developing products is one of the enterprises' great competitive gains nowadays, and it is directly connected to the consumers' yearnings and necessities.

In this context, product complexity is currently one of the main challenges with which manufacturing management has to deal, especially when it comes to factory performance and efficiency. Therefore, knowing and understanding the elements that influence this complexity well is a key point to companies that design and launch new products on the market. Thus, the complexity management must become the nucleus of superior capacity and differentiation of the companies that deal with it (Schleich & Schaffer, 2007; Badrous, 2011; Ramdas, 2003). And according to Perona & Miragliotta (2004), the control and management of the growing level of complexity must be considered a strategic matter to enterprises, which reinforces, even more, the importance and necessity of knowing and detailing the complexity that within the production environment.

With that said, enterprises that are able to successfully manage their product development and effectively deal with product complexity have a head-start in the race for competitive advantage on the consumer market (ElMaraghy et al., 2012). However, for a better management of this complexity within the systems and, therefore, a better factory performance, first, it is necessary to know what effects the product complexity may cause in the manufacture and in its productivity. In view of this, this work aims to propose a dynamic simulation module to verify the effects the increase or variation of product complexity may cause in the manufacturing productivity over time.

1.1 Methodology used in the research

This present research has used the inductive method, supported by exploratory research of the subject, which allowed for guidance in the recognition and analysis of the effects of the product complexity in productive systems. In order to make the study problem more explicit, a bibliographic research was held, which allowed for a greater familiarity with the research problem. These investigations, based on scientific publications of the subject related area, emphasize even more the characterization of an exploratory research (Lakatos & Marconi, 2007).

Regarding the approach used in the development of the work, it can be characterized as partially quantitative, a fact commonly used within researches in the area of exact sciences, such as engineering. However, the research also displays qualitative characteristics, when based on a subjective interpretation of facts, being interpreted by not only numbers but also logical and observational tools.

When it comes to the steps used to reach the research objective, a bibliographic research was held, allowing for analysis and identification of concepts, elements, and impacts regarding product complexity, all of which contributed to the structuring and development of causal diagrams which preceded the proposed model. In sequence, by applying system dynamic concepts with the creation support of the Vensim® PLE (Version 6.3) software, the dynamic simulation model and its respective flow and stock models were developed. With this, an exhausting set of simulations were conducted with the intent of verifying the effects the increments in product complexity may cause in manufacture.

2 Complexity and its definitions

Complexity has been discussed in Physics, Biology, Philosophy, Engineering, Management, Health, Sociology, among others (Bozarth et al., 2009; Suh, 2003, 2005). Originating from the latin word "Complexus", which means "That which is woven together" or "encircling", complexity can be interpreted in various ways. Badrous (2011), for instance, understands complexity as a set of different yet related elements, or even something hard to understand because of its various distinct and interconnected parts. On the other hand, Giovannini (2002) says it can be understood as something that covers many elements or parts, as well as a set or group of things that have any sort of link or nexus between themselves.

However, there have been many attempts at creating a universally accepted definition of the term complexity. In spite of that, this general, unique and universally accepted definition is still under construction, for these definitions are as diverse as the authors who developed them, such as (Blecker et al., 2004; Jacobs, 2007; Ramdas, 2003; Schleich & Schaffer, 2007; Wu et al., 2007; Lee, 2003; Suh, 2003; Rodríguez-Toro et al., 2003).

In line with these statements, Morin (2010), Lee (2003) and Rodríguez-Toro et al. (2003) claim that complexity can't be reached through a previous definition. It is necessary to follow such diverse ways that researchers must ask themselves whether or not there are "complexities" and not just one "complexity".

A topic which deserves discussion regarding complexity and its innumerable definitions is distinguishing it from the term complicated and not considering these two terms as synonyms. This statement can be justified on the basis of discussions shown by Suh (2003), Perona & Miragliotta (2004), who converge their thoughts when characterizing complicated as a set of woven parts or elements that can be analyzed separately in order to obtain a relevant solution for the complicated itself.

However, complexity goes far beyond a set of woven parts or elements that can be analyzed separately. Based on already presented statements from Morin (2005, 2010) and Wang (2010), it can be understood as a system composed such woven elements that a separate analysis of these elements is nearly impossible.

2.1 Product complexity

The product is the link of the enterprise and it is around the product and the dynamics of this relationship that the manufacture can suffer the consequences of the complexity being involved in this business system. In view of this, some concepts, explanations, and discussions regarding product complexity can be obtained in literature. The most relevant ones to this work will be presented below.

Some authors (Jacobs, 2007; Pasche, 2008; MacDuffie et al., 1996; Ramdas, 2003; Gupta & Krishnan, 1999; Closs et al., 2008; Suh, 2003; Lee, 2003; Schulz, 2008; Kaski & Heikkila, 2002; Rodríguez-Toro et al., 2003; Zhu et al., 2008) understand product complexity under the analysis of four elements that characterize it: number of components, componente variety, number of interactions and amount of interactions among components.

In addition to this understanding, Jacobs & Swink (2011) clarifies this comprehension of product complexity can also be applied to the analysis of the complexity of other systems, such as a production system, for example. This way, various products are chosen as system components, as well as the various kinds of interaction that there can be among them.

Through a more focused view of the structure of the product, and as a complement for the comprehension exposed on the previous paragraph, authors (Bliss, 2000; EIMaraghy & Urbanic, 2004; Suh, 2003; ElMaraghy et al., 2005, 2012) state that the quantity and the various types of materials and geometries that components present are features that can also influence the increase in the complexity, since they can be considered new components to be inserted in the product. Still, in this context, Hobday (1998) states that product complexity can also be characterized based on the technologic innovation degree and variety of knowledge basis that companies have on the product. Furthermore, Kotteaku et al. (1995) points that this complexity can be provided by four dimensions related, respectively, to the technical structure of the product, its technological differentiation, necessary facilities for development and after-sale services.

Therefore, based on the presented discussion, for research purposes, product complexity is characterized under four main elements: number of components, the component type of feedstock, component geometry and interactions among components, as shown in Figure 1.

It is reinforced that the number of components is connected to the number of components a product has in its structure, and they can be identical or not, but already known and applied in processes of production. This leads to the two other characteristics of product complexity: component feedstock and geometry, which are responsible for the variety of components in the products. Given the need, for instance, in a certain product, for the use of plastic, metallic components, among others, as well as the need for items that could even have the same the same types of material, though with different geometries, which implies varied sizes, shapes, and dimensions. Thus, they can be understood as features that enable distinction in a product, while being considered new components to be adopted in its structure (ElMaraghy et al., 2012; Closs et al., 2008).

Finally, interactions among components are related to the existing links between components of a product, which generate a reciprocal influence. In other words, it regards the existing connection between two or more components. These connections need to be physical, such as mechanical, pneumatic and information connections, given the necessity for force transfer between components (ElMaraghy et al., 2005; Kaski & Heikkila, 2002).

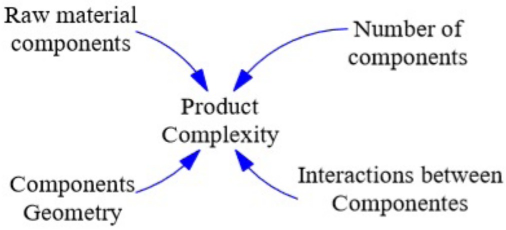

Figure 1. Elements that characterize product complexity. Source: The author.

2.2 The effects of product complexity in the productivity

Within productive systems, there are various complexities which are capable of self-influence, based on the interactions between them (Bliss, 2000; Jacobs, 2007; Suh, 2003, 2005). One of them, product complexity, is able to cause several effects in the whole production system and in its elements, which affects the other existing complexities. With this, Danilovic & Browning (2007), Jacobs (2007) and Pasche (2008) state that product complexity not only influences manufacture elements but is also influenced by them throughout the whole production process, as shown in Figure 2.

To Pasche (2008), product complexity is a result of its developing actions due to decisions of the PDP staff. The author further states that the project and development staff should know the true needs and wishes of the consumer market, since these needs are the foundation to the variation of product complexity, besides having mastery over new technologies and creative capacity to propose simple project alternatives of less complexity.

On the other hand, other authors (Danilovic & Browning, 2007; Suh, 2003, 2005) state that the product development sector cannot measure, identify or have a notion of costs and impacts that the complexity inserted in the products may cause in the production system as a whole. Accordingly, Kinnunen, (2006) and Shibata et al. (2003), based on empirical tests, state that there is usually a steady drop in the productivity of the systems as the complexities of the product, process, and manufacture increase. Regarding productivity, Ferreira (2003) states that it can be considered as one of the simplest results to be obtained, yet the most important to production management.

Still, in this context, Ferreira (2011) and Alberton (2006) state that although productivity has its concept presented under several perspectives, its main idea always comes back to the relationship between production and one or more of its inputs factors used. Accordingly, various authors (Liker, 2005; Martins & Laugeni, 2005; Meredith & Shafer, 2002; Nito, 2003; Silva, 2010; Ferreira, 2003, 2011; Alberton, 2006; Carvalho, 2002) state that productivity can be defined as the relationship between what has been produced by a system and the inputs, in real terms, used to achieve what has been produced, such as money invested, manpower employed, production time, among others.

With this, after also analyzing the Figure 2, it is noticeable that the increase in product complexity generates direct impacts in the variety within three important components of the production system: Its processes, its suppliers and the resources necessary for execution and production. It can also be noticed that these impacts come from two types of complexities: the necessary and the unnecessary. The necessary is related to the product increments due to the goal of meeting the clients' needs, while the unnecessary can be understood as the increments created in the products by the company and won't be considered important by clients who will make use of the product (Danilovic & Browning, 2007).

The changes that can be made in the products are countless, and they will contribute in a direct manner to the increase or decrease of the complexity, and consequently, the generation of effects within production systems. Several authors (Bozarth et al., 2009; ElMaraghy et al., 2005, 2012; MacDuffie et al., 1996; Badrous, 2011; Zhu et al., 2008; Jacobs, 2007; Blecker et al., 2004; Hobday, 1998; Kotteaku et al., 1995; Rodríguez-Toro et al., 2003; Dalgleish et al., 2000; Eskilander, 2011; Wang et al., 2011; Bliss, 2000; ElMaraghy & Urbanic, 2004; Suh, 2003; Danilovic & Browning, 2007; Lee, 2003; Schulz, 2008; Closs et al., 2008) present, in their works, the most diverse effects that increasing one of the four elements that characterize product complexity, as shown in Figure 1, can cause in production systems.

So, given the idea convergence of all authors mentioned in the previous paragraph, Chart 1 was structured and it displays the effects that the increments in product complexity can cause in manufacture. From Chart 1, it can be noticed that increasing one of the elements of the product complexity can induce possible changes in the operation time of production processes. Therefore, the increase or decrease of

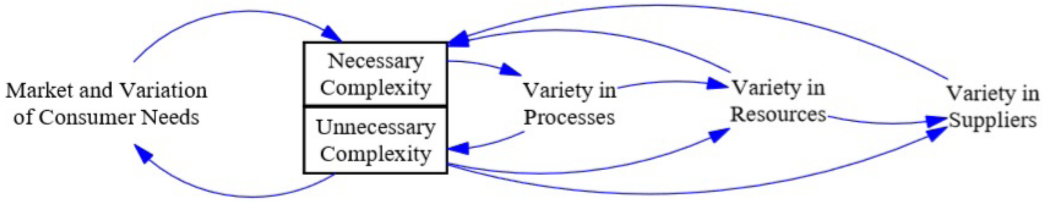

Figure 2. Product complexity and its influences within manufacturing. Source: Adapted from Danilovic & Browning (2007), Jacobs (2007) and Pasche (2008).

Chart 1. Effects of product complexity in manufacturing.

Elements that characterize product complexity	Authors	Effects caused in manufacturing
Number of Components	Jacobs (2007); Badrous (2011); MacDuffie et al. (1996); Bozarth et al. (2009); Wang et al. (2011); Danilovic & Browning (2007); Lee (2003); Schulz (2008); Zhu et al. (2008); Bozarth et al. (2009); Blecker et al. (2004); Closs et al. (2008).	- Increase of process cycle duration; - Increase of production *lead time*; - Increase of product crossing duration; - Need for new workstations; - Need for extra hours; - Need for new work shifts; - Need for more manpower; - New hires; - Increase of production costs; - Need for new processes; - Increase of product stock level; - Increase of the number of product components necessary in stock; - Increase of rework and inactivity rates of the production line.
Feedstock of Components	Wang et al. (2011); Zhu et al. (2008); MacDuffie et al. (1996); Bozarth et al. (2009); Badrous (2011); Lee (2003); Schulz (2008); ElMaraghy et al. (2012); Danilovic & Browning (2007).	
Geometry of Components	Dalgleish et al. (2000); Badrous (2011); Zhu et al. (2008); ElMaraghy et al. (2012); Rodríguez-Toro et al. (2003); Lee (2003); Eskilander (2011); Danilovic & Browning (2007); Schulz (2008).	
Interactions between Components	Closs et al. (2008); Blecker et al. (2004); Zhu et al. (2008); Danilovic & Browning (2007); Wang et al. (2011); Badrous (2011); Bozarth et al. (2009); Jacobs (2007).	

Source: The author.

production processes end up directly impacting system productivity, for the more time for a specific processing, the lower the production speed that the system will present, which is a direct cause of the productivity reduction (Nito, 2003; Silva, 2010; Carvalho, 2002).

Thus, for research purposes, the productivity of the system will be analyzed through the number of products that the process is able to produce in a predetermined period of time, according to Equation 1.

$$Line\,Productivity = \frac{Obtained\ production(units)}{Production\,time(hours)} \tag{1}$$

However, some authors (Nito, 2003; Silva, 2010; Carvalho, 2002) state that there are various ways to analyze the productivity of a production system. Nevertheless, the proposed model is a dynamic simulation model, which uses the precepts and logic of system dynamics to analyze the behavior of variables over time. Therefore, Equation 1 is the one that best fits for the analysis of the system productivity, once it will allow for verification of the production line's productivity behavior, while the increments of the product complexity will be inserted in the proposed model.

3 The proposed model

The developed model was based on the generic model of Figure 3 by Sterman (2000). It displays the main elements that a structure of production of goods should present, encompassing elements from raw data collection of market demand, through the "Clients' Request" variable, to planning through the "Demand Prediction" variable. Then, all the process through which the product will go through can be noticed, starting from the "Production Input Rate" variable, which will be responsible for the entry of inputs in the production process, and giving, as a result, the number of manufactured products through the "Product Output Rate" variable. The "Product Output Rate" will be responsible for product supply in the "Final Product Stock" variable, and the process will be concluded with the "Product Delivery" variable, which will present the number of items withdrawn from the system and delivered to the market.

The proposed model uses constant interactions between the adopted variables, which allows for the creation of non-linearity in models which use system dynamics. These interactions between variables can be seen in Figure 4, which displays the causal diagram developed and used a the foundation for setting up the simulation model.

The diagram in Figure 4 displays the control and feedback cycles that are within the system and provide maintenance and balance of its running. Regarding the information input on the Figure 4 diagram, it must be emphasized that it will happen through the "Market Demand" variable, which is also responsible for the system's product output through its influence on the "System's Product Output" variable. In addition to these interactions, it is worth highlighting the existence of time lags the diagram has, representing the delays, which are responsible for the dynamic behavior of the systems (Santos, 2006; Sterman, 2000).

On the diagram displayed in Figure 4, the delays are represented by the letter "D" in the connection arrows between the elements. These delays correspond to the elapsed time period for the behavior changes to take place in the variables. Thus, these time intervals are necessary, once these changes are not immediately felt in the system, hence the time intervals for changes to occur.

The proposed model was structured as shown in Figure 5, and it was based on the causal diagram of Figure 4, the application of flow diagrams and available stocks in the software Vensim® PLE (Version 6.3), and some differential equations for the creation of dynamic environments.

It consists of two large linked blocks, where each one has its own set of variable stocks and flows and represents a generic production line, which enables the manufacturing of different products. The model also considers that the complexity of the products is due to changes in the elements that characterize it, and these changes will be felt through shifts in the processing time in them.

With this, aiming at a better understanding of the modeling, Figure 6 shows a causal diagram that

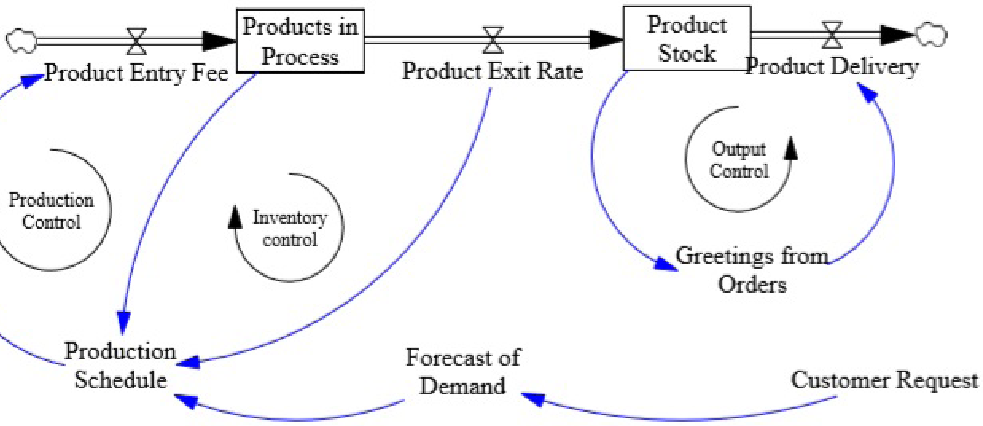

Figure 3. Generic Model for a Production System. Source: Adapted from Sterman (2000).

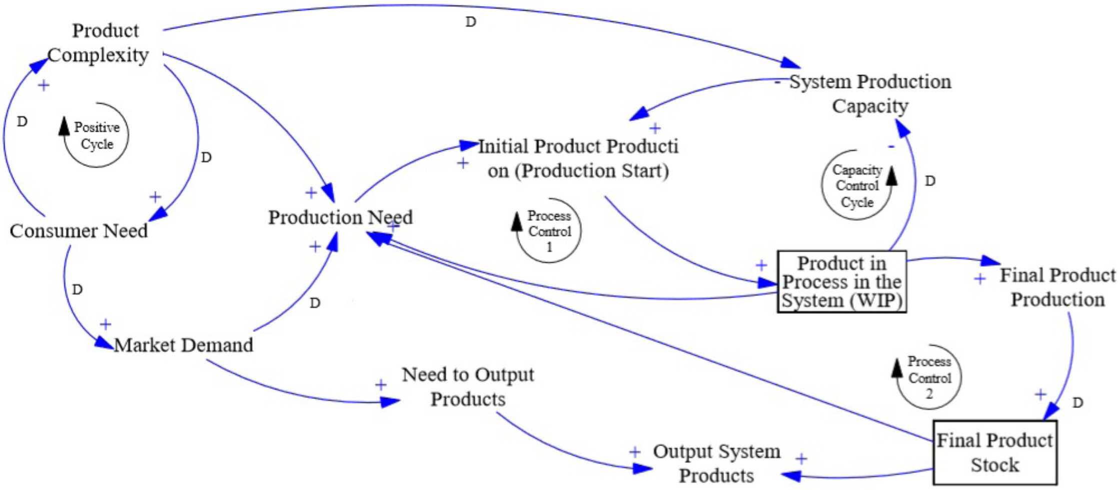

Figure 4. Proposed Model's Causal Diagram. Source: The author.

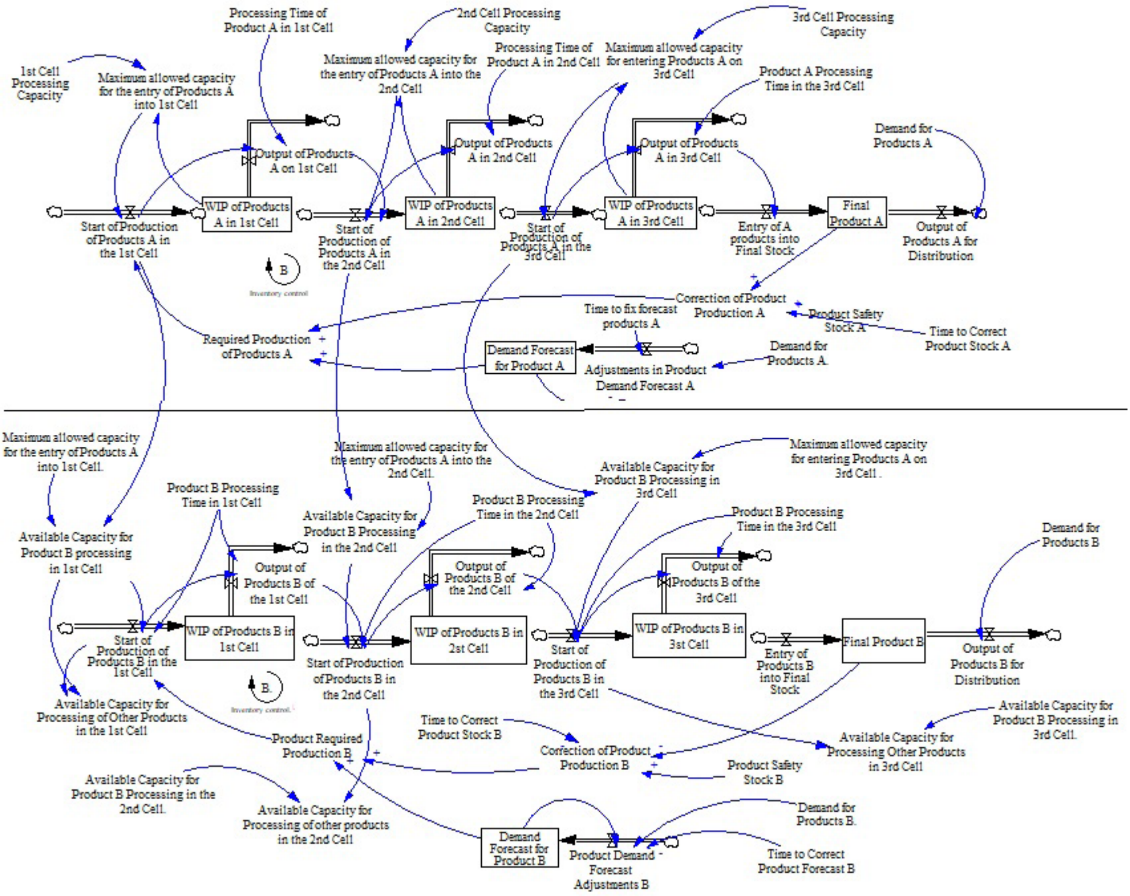

Figure 5. Proposed Model. Source: The author.

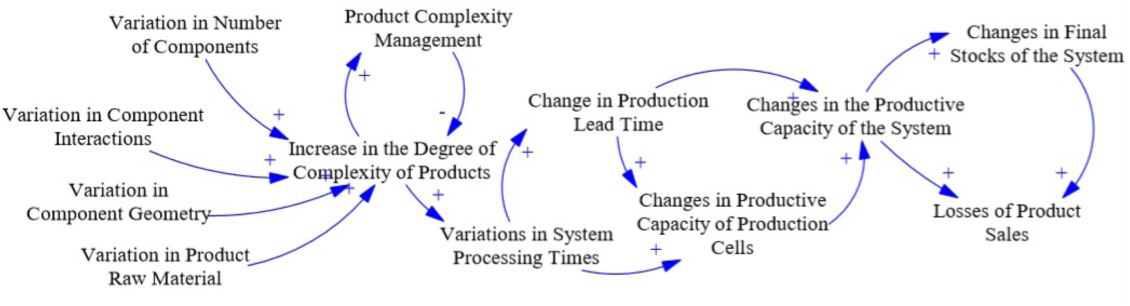

Figure 6. Effects of Product Complexity on the Productive System. Source: The author.

illustrates where the effects caused by the variation in the product complexity can be felt within the model. Also, there is the intention of showing where the increment of the product complexity is inserted into the model, given its changes made by the product development staff.

Regarding the variables that are part of the proposed model, Chart 2 displays a brief description of each of the model's variables, aiming at a better understanding of its structure and interaction logic.

4 The effects of product complexity in productivity

In order to analyze the complexity degree of the products, the existence of a certain product was used, and this product has a standard complexity "1", which consists solely of components and interactions already used in the process. Because the work considers that the gradual increases in the elements of the product complexity can affect the time in the process and its

Chart 2. Description of Model Variables.

Variables of Analysis	Definition	Influenced Variables
Product Demand	Number of products demanded by the company.	Product Demand Forecasting
Product Demand Forecasting	Number of adjusted requests, based on the company's expectations.	Demanded Product Production
Demand Forecasting Adjustments	Necessary demand adjustments, based on a variation rate stipulated by the organization over time.	Product Demand Forecasting
Product forecasting Correction Time	Necessary duration for the variations in demand to be felt in the organization.	Product Demand Forecasting
Demanded Product Production	Number of necessary products, given a constant update based on the number of requests already in stock.	Production Start of Products in Cell
Production Start of Products in Cell	Number of products that enter the production cell for processing.	Cell Product Output; WIP of Products in Cell
WIP of Products in Cell	Number of products undergoing transformation in the cell.	Cell Product Output; Maximum allowed Capacity for Production Start of Products in Cell
Cell Product Output	Number of products processed by the production cell.	Production Start of Products in Cell; Product Input in Final Stock
Maximum allowed Capacity for Product Input in Cell	Possible number of inputs that can enter the cell to be processed at a given moment, given the number that is already in process.	Production Start of Products in Cell
Cell Processing Capacity	Maximum number of products the cell is able to process. This value is usually estimated by the nominal capacity of the equipment in the cell.	Maximum allowed Capacity for Product Input in Cell
Product Processing Time in Cell	Necessary time for the product to be concluded in the cell, given the processes through which it must pass.	Cell Product Output
Available Capacity for Product Processing in Cell	Number of products the cell can still process, given its current use in a given moment.	Production Start of Products in Cell
Product Input in Final Stock	Number of finished products that go into stock for distribution and/or storage.	Final Product Stock
Final Product Stock	Number of finished products in stock in the system.	Product Output for Distribution; Product Production Correction
Safety Stock	Minimum number of products in stock the system must have.	Product Production Correction; Final Product Stock
Product Production Correction	Number of products that must/mustn't be inserted in the demanded production, aiming to maintain enough stock to attend the company's necessities.	Demanded Production of Products
Product Stock Correction Time	Necessary time duration for stock variations to be felt in the system and corrected.	Product Production Correction

Source: The author.

operation, there is an associated standard time for each of these components.

With this, in addition to setting a standard duration for each one of the components that make up the product structure, the proposed model's production cell in which the components are processed was also set. Following these steps allows for knowing the changes that the increase in the complexity can cause in each production cell, and they will be the foundation for simulations and tests with the model. Thus, there were two simulation groups. In the first one, the effects that product complexity can cause in system productivity were verified, disregarding the presence of possible capacity restrictions. In the second group, capacity restrictions were taken into consideration to analyze the effects of complexity increments.

4.1 First analysis group

For this simulation group, it is considered that there are no capacity restrictions and there is the production of a product with a standard complexity "1", which consists solely of standard components and interactions. The components are responsible for 54% of this complexity, while the interactions represent 46%. Therefore, the standard complexity of the product does not have, in its composition, components with different geometry or feedstock.

Based on this product, the presented simulations were developed by applying successive 10% increments in the overall complexity of the standard product until the product doubled its standard complexity. However, these successive increments were applied in different ways. In a first way, each 10% increment in the complexity caused similar changes in each one of the three production cells. In a second way, the increments generated different changes in each cell.

After that, three new ways for the complexity increments were applied, and in these ways, the successive 10% increments only caused initial changes to the first production cell and the remaining cells with no alteration. Shortly after that simulation, the increments were repeated, but this time, only the second cell underwent changes, and after, the third one.

It is important to emphasize that, in order to develop all the simulations mentioned in the previous paragraph, the following values for the exogenous variables of the proposed model were used:

- Product Demand: 100 units;
- 1st Cell's Processing Capacity: 100 units;
- 2nd Cell's Processing Capacity: 100 units;
- 3rd Cell's Processing Capacity: 100 units;
- Safety Stock: 0 units.

With these considerations in mind, Figure 7 shows, in one graph, the productivity curve obtained through all the simulations done in this group.

From the results of these simulations, it can be noted that the productivity of the system regarding the production of the product with standard complexity "1" is 4 units/hour, therefore, with this initial productivity, the system is able to produce the requested demand in 25 (twenty-five) simulation hours. However, when analyzing system productivity as the first 10%-complexity increase is added to the product, causing similar changes in the three cells,

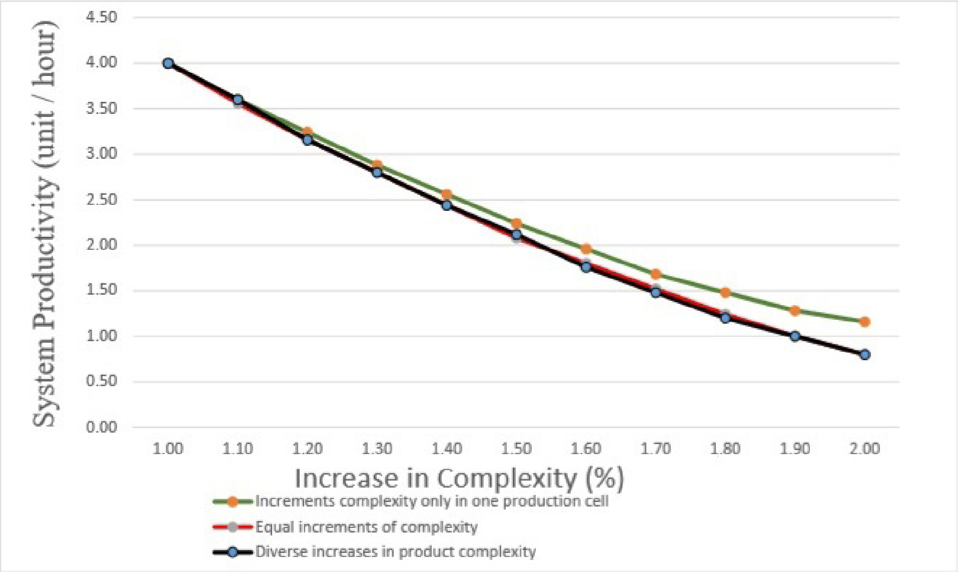

Figure 7. Behaviors obtained with all the variations in the product complexity. Source: The author.

it is noted that the system productivity drops down to 3.56 units/hour, which represents an 11% loss in productivity. At the end of these increments, it can be seen that doubling the complexity was able to cause a 53.1% loss in process productivity, which makes the production line unable to produce the requested demand.

After analyzing the results displayed in Figure 7 and regarding productivity behavior before complexity increase being able to cause different changes in each one of the cells, it can be noted that doubling the complexity resulted in the system productivity having a production reduction from 4 to 0.80 units/hour, which implies in a 53.3% loss in productivity.

For these first two results, it is noticeable that the decreases in productivity display very close values: 53.1% for similar changes and 53.3% for different ones. Based on these results, it can be noted that productivity is mainly affected by the complexity increment that is applied to the product, and not by its distribution within the process. Thus, an exhausting set of new simulations was done, in which the increases in the complexity of the standard product caused changes in only one of the production cells.

As a result of this new set of simulations, there was a 48.5% loss of overall productivity coming from the production of a product 100% more complex, leading to a decrease in production from 4 units/hour to 1.16 units/hour. When compared to the productivity fall obtained in the first simulations, in which the increments in product complexity cause changes in all three production cells, it can be noted that the productivity fall was greater, displaying a 53.2% loss, that is, an average productivity gain of 4.7%.

These different productivity results happen, first, because the system has 30% of idle capacity, therefore not operating in its maximum production limit. So, when the complexity increase alters the production process of just one cell, the production delay is felt solely in that particular cell, while the other ones will keep producing in a faster way than the affected one. Still, when the complexity increase changes the process of the three cells, a proportional delay will be felt in all of them, turning the whole process slower. This implies that there will be a lower production rate of products per cell, which leads to a greater overall productivity fall of the system.

4.2 Second analysis group

After demonstrating that the increments in complexity affect system productivity without the presence of possible capacity restrictions, the simulations presented in this new set were developed with the purpose of analyzing the effects in productivity, but now taking into consideration the presence of restrictions in the production capacity of the proposed model's cells.

Regarding the values used for the exogenous variables of the proposed model, it is highlighted that these values used for the requested demand of the product and for the safety stock. However, the variables related to the cells' processing capacity were changed to minimum values, which allowed for the production of the entire requested demand, that is, 100 units of products.

For this, an exhausting set of simulations was developed until the minimum capacity each cell must have was determined, targeting the entire requested demand production at the 25-hour duration, as mentioned before. With this, the minimum capacity to produce the entire demand with no productivity loss of the standard product was obtained, and it is 40 units of products in process per production cell.

Thus, if the production capacity of any cell is below the displayed value, the system will not be able to maintain its production at the same productivity rate. For instance, when arbitrating the processing capacity of one of the cells in a value of 39 units, simulations showed that the system presented a productivity of 3.92 units/hour, which implies a 2% productivity reduction.

Therefore, for the first set of simulations, there was a 10% capacity reduction only in the first cell, and in sequence, the same procedure was conducted for the second and third cells. As the first cell has a 10%-lower capacity than the others, two types of complexity increments were inserted. In the first type, the increment caused similar changes in all the cells, whereas in the second type, different changes. Figure 8 shows the behavior obtained with the two sets of simulations performed.

In the simulations in which the changes caused by complexity were felt equally by all cells, there was a 59.6% drop in process productivity, while for different changes in the cells' processes, there was a productivity drop of 59.4%. When comparing to the results obtained from the first simulation group, it can be noted that the presence of the constraint in the first production cell contributed to an average system productivity reduction of around 6.3%.

Through these results, it was sought to understand what the effect caused in the system was when the increment in product complexity induces changes only in the production cell that presents a 10%-capacity reduction. Then, there was also the analysis of the system's behavior when these increments happen only in the cells that don't display capacity reduction. With this in mind, more than two hundred simulations were conducted, in which the production constraint and the possible changes product complexity may cause in one cell were altered, in order to understand the general behavior the productivity presents. Thus, Figure 9 displays a concatenation of the main results

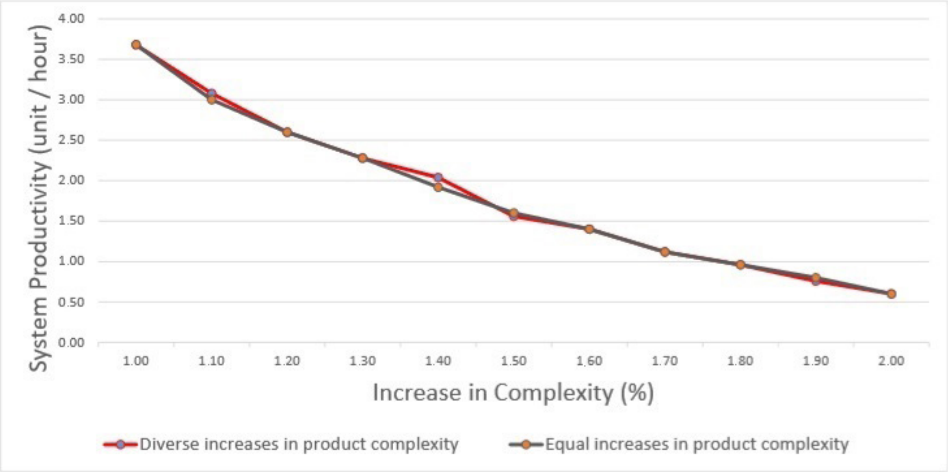

Figure 8. Productivity Behavior, with the first cell being constraint. Source: The author.

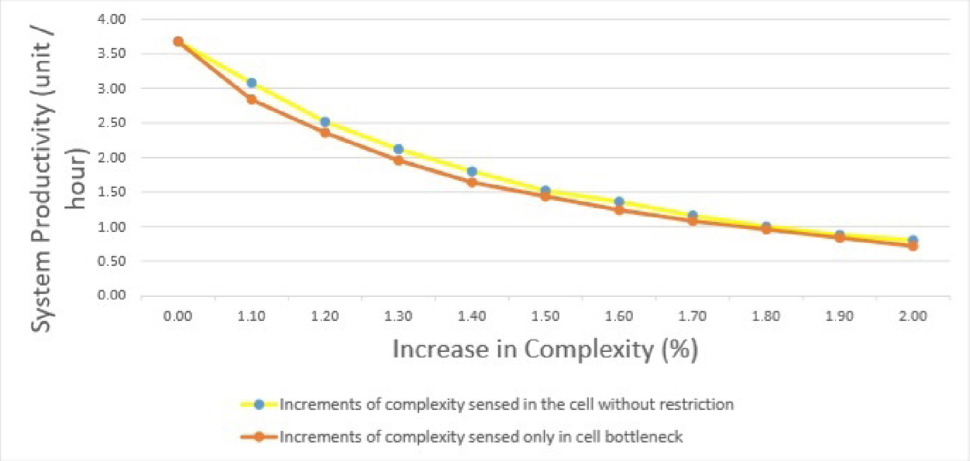

Figure 9. Productivity with complexity increments felt on both cell types. Source: The author.

obtained from the performed analysis in one single graph.

Through Figure 9, it can be seen that the presence of a restriction, along with increments in just one production cell, causes a 62.2% productivity fall, that is, a loss of more than half of the system capacity. On the other hand, when the increment and the restriction are not present in the same production cell, the system also cannot produce the whole requested demand, which causes a 59% productivity drop.

When analyzing the first results obtained from the simulations, and considering only the complexity increments obtained from the first simulation group, it can be noted that the presence of the constraint in at least one of the production line cells, along with the complexity increment, caused a 14.5% reduction in the entire system productivity. With this reduction, the system productivity becomes an average 1.63 products/hour, therefore the system is only able to produce about 40% of the requested demand, which means that more than half the planned production won't be delivered to the market.

However, when analyzing the effects generated by the presence of restrictions in the system, with the complexity increments just altering the cells' processes at the constraint, the reduction of system productivity drops by an average 10%, when compared to the simulations of the first group. With this, it is noticeable that both the capacity restrictions and the complexity increments are able to impact system productivity, but these impacts are most strongly felt by the increase in product complexity.

Thus, the new-product-development staff, when planning or designing a more complex product, must analyze the elements that provide a greater complexity in the product as well as the spots within the production process in which these new increments cause changes that may harm the system production capacity.

With that said, the product development staff will not only be focused on attending consumers' needs but also analyze the best way in which this new product can be processed without its new complexity causing greater losses in the process. This statement converges with the statements already presented by various authors (Perona & Miragliotta, 2004; Schleich & Schaffer, 2007; Badrous, 2011; Ramdas, 2003), as they emphasize that complexity must become the nucleus of superior capacity and differentiator of companies in front of competition, controlling the increasing complexity level of products and distributing it within the factory environment in an effective manner.

So, the increment in the complexity of products will be able to cause, in the process or production line, the creation of new operations for the product to be fully made. And this increment of new operations may imply a series of effects in the system, such as the requirement of extra hours for the demand conclusion within the maximum amount of time. However, the complexity increment may affect the process in such a way that the system productivity is guaranteed only by the creation of a new work shift overnight, which leads to the necessity of more manpower, equipment, and feedstock.

Regarding the performed simulations, it is important to emphasize that there was, in the production system, more than one constraint cell, which displayed similar results to the already obtained ones. This is due to the fact that the production system is already operating in its production limit, and therefore the presence of a constraint is already enough to cause productivity reduction.

Another topic approached in the various simulations was the use of capacity restrictions over 10%, with the results being directly proportional to this capacity restriction. Thus, the effects of the increments in product complexity will be the same in the process, with the production loss only being proportional by the new restriction imposed to the system.

5 Conclusions

This research contributed to the study and analysis of product complexity and its effects on production systems through the development of a simulation model to verify the effects generated by the product complexity in the manufacturing productivity. When it comes to studying complexity, based on all the bibliographic survey done, it can be concluded that its concept and definition are abstract and generalist due to the various points of view each researcher has about it.

In a similar way, it was also noted that product complexity does not have a unique and universally accepted concept in literature since its scope and definition are defined based on each researcher's specific goal. However, even after all presented concepts, product complexity is usually characterized and studied under four main elements that mold the structure of new products.

Regarding the effects the complexity can cause in the manufacturing productivity, it is concluded that the successive complexity increments in the products induce a direct reduction in process productivity. That way, these productivity drops directly impact the number of products made by the system due to its production speed reduction. Thus, this speed reduction affects not only the attendance of the demand requested by the consumer market within a pre-established deadline but also other topics, such as the number of workstations, new production shifts, extra hours, among others.

It is also concluded that previous knowledge of the production process and the points in which there may be possible capacity limitations is essential to obtain better results for the system productivity. Once increments in product complexity that cause significant changes in constraints of the process can generate greater production losses in the entire production process, it can be concluded that the additive increments in product complexity can induce lower drops in manufacturing productivity if managed in a strategic manner. That is, also taking into consideration the characteristics inherent to the production process.

When it comes to the possibility of future works, there is the consideration, within the proposed model, of factors external to the organization, such as market analysis and possible reasons for demand oscillations of the simulated products. Another topic of possible work is the development of simulation models that allow for the structuring and analysis of the effects caused in the processing duration of products, which are due to possible point changes in each one of the elements that characterize the product complexity.

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