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# Complexity Measurement in Two Supply Chains with Different Competitive Priorities

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**Abstract**: Complexity measurement based on the Shannon information entropy is widely used to evaluate variety and uncertainty in supply chains. However, how to use a complexity measurement to support control actions is still an open issue. This article presents a method to calculate the relative complexity, i.e., the relationship between the current and the maximum possible complexity in a Supply Chain. The method relies on unexpected information requirements to mitigate uncertainty. The article studies two real-world Supply Chains of the footwear industry, one competing by cost and quality, the other by flexibility, dependability, and innovation. The second is twice as complex as the first, showing that competitive priorities influence the complexity of the system and that lower complexity does not ensure competitivity.



*Keywords:* Supply Chains; Complexity; Complex Adaptive Systems; Dependability; Reliability; Flexibility; Innovation; Variety; Uncertainty; Footwear Industry.

## 1. INTRODUCTION

Linear cause-effect relationships are not sufficient to explain all the phenomena resulting from the complex interactions that arise in collaborative arrangements (Dekkers, 2017) such as supply chains (SC). For instance, in an SC, a phenomenon that entails non-linear relationships is 'coopetition', i.e. when companies cooperate by sharing unique or difficult-to-acquire resources, such as infrastructure or skilled labor, and at the same time compete for abundant resources such as the consumer market and raw materials (Sellitto et al., 2018a).

Innovation, flexibility, dependability, and eco-efficiency challenges usually create non-linear relationships between players, even if they are competitors. As innovation requires resources that are difficult to obtain, companies can cooperate in their procurement, as in technology clusters. To achieve eco-efficiency, a company may use the waste of another company as raw material or fuel, as in eco-industrial parks. The same is true in terms of flexibility and dependability (Sellitto et al., 2018b). Non-linear relationships between companies belonging to some types of business arrangement result in a certain degree of organizational complexity. The measurement or evaluation of this complexity has motivated recent studies. This study focuses on the supply chain (SC) complexity and in the supply chain management (SCM).

There are studies on organizational complexity in the SC and in the SCM in the literature. Some studies focus on complexity measurement while others focus on specific concerns or applications. A search in the Science Direct database in November 2018 with the keywords "complexity in supply chains" in the title, abstracts, or keywords resulted in 258 articles from 2006 onwards. In the last five years (2014 to 2018), there have been 138 articles. A more conservative search comprising the keywords "supply chain complexity" only in the title resulted in eleven articles since 2009. Some articles deal with facets of the complexity such as tools to obtain specific results or avoid specific threats, such as disruption risks (Wang et al., 2018), environmental strategies (Kinra and Kontzab, 2008), flexibility in products and processes (Blome et al., 2014), variety of products (Daie and Li, 2016), and risk management (Ge et al., 2016). Other articles analyse the structure of the complexity in SCs (Cheng et al., 2014), complexity drivers (Chand et al., 2018; Serdarasan, 2013), complexity implications on SC performance (Lyons-White and Knight, 2018; Bozarth et al., 2009), and complexity as a specific measurement tool (Cagliano et al., 2009).

This article presents a method to measure the complexity in an SC. The research question is how should the complexity of an SC be measured? The implications, drivers, and consequences of the complexity on the performance of the SC are outside the scope of this article and will be covered in future studies. The research method is quantitative modeling. The research object is two SCs from the footwear industry located in Southern Brazil with different structures and priorities. The main theoretical foundation is the Shannon information entropy, which calculates the amount of information required to describe a complex object. The main

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contribution of the article is the method, to be replicated in further, more extensive studies.

## 2. BACKGROUND: SC COMPLEXITY

The concept of complexity is present in natural sciences, such as physics, biology, and ecology, as well as in social sciences, such as management, economics, and anthropology. Due to the diversity of interests, it is difficult to create a comprehensive definition of complexity (Isik, 2010).

Our study starts with the definition adopted by Bar-Yam (1997), which refers to the quantity of information required to describe the interactions and mutual interferences among the parts of a complex adaptive system (CAS). This definition is in line with the seminal definition of a complex system posed by Simon (1962), as an object composed of a large number of parts, which interact and influence each other in different degrees and in non-linear relationships. Another seminal definition (Yates, 1978) states that a complex system exhibits a significant number of significant non-linear interactions among parts.

Our study assumes that complexity is independent of the size, the number of parts, and the difficulty of the mission of the system, but depends on the variety and the intensity of the mutual interactions. A large, sophisticated object such as a wind generator or a diesel engine may be complicated but not complex. An SC, an eco-park, or a technology cluster in which a few companies require mutual, intense interactions, is a complex, even simple object. Another assumption is that the more complex a system is, the more information it requires. Consequently, if a given metric provides the amount of information embedded in a system, this metric also informs on the complexity of this system.

The non-linear behavior makes the response of a complex object to an external stimulus almost unpredictable, even if the subjacent relationships are quite simple to understand. The bullwhip effect is a good example of unpredictable behavior in SCs, which emerges from a simple rule. In the bullwhip effect, small, predictable movements in consumer demand create large, hard to anticipate changes in the size of the orders that suppliers have to meet (Wang and Disney, 2016).

The complexity also lies in the uncertainty between the interactions and the amount of disorder and order that coexist in the object. In statistics, the order of the populations can be identified by observing the disorder of the samples. In complexity, interacting parts generate behaviors that do not exist in the isolated parts. This emergent behavior disappears if the parts separate again. In short, it is not possible to understand the complexity of an object by samples or by isolated parts, but only by the whole and the interactions within the whole (Morin and Le Moigne, 1999; Ruelle, 1993).

Our study focuses solely on the complexity of SCs. Measuring or evaluating the complexity in an SC may contribute to the manageability and controllability, which is a key element especially in globalized SCs (Isik, 2010). Our study relies on the Shannon information entropy, a consistent metric that provides the amount of information in an object, which is useful for measuring the complexity of an SC (Ruiz-Hernández et al., 2019).

The Shannon information entropy in SC complexity is not a novelty. The information entropy has helped in measuring the knowledge regarding the risks of shortages and pitfalls under uncertainty in the relationships between the members of an SC (Kriheli and Levner, 2018). The information entropy has also helped to formulate a unified index for the complexity in manufacturing, based on the mix of products (Hu et al., 2008), as well as describing the exchanges of materials and goods between companies in an SC (Allesina et al., 2010).

The $H(p_i)$ information entropy was firstly defined by Shannon (1948) according to equation (1).

$$H(p) = -\sum_{i=1}^{n} p_i.\log_2(p_i) \quad (1)$$

in which $p_i$ is the probability of the occurrence of the $i_{th}$ out of $n$ possible outcomes and $\sum_{i=1}^{n} p_i = 1$.

The literature recognizes three flows in the SC that drive complexity, the materials, information, and financial flows (Levner and Ptuskin, 2018). Regarding the material flow, Hu et al. associated the SC complexity with the variety of products in the manufacturing stage (Hu et al., 2008). Other studies have associated SC complexity with product complexity (Eckstein et al., 2015), the product mix combined with the product structure (MacDuffie et al., 1996; Fujimoto et al., 2003), and the possible configurations in scheduling and rescheduling the manufacturing system (Deshmukh et al., 1998; ElMaraghya et al., 2005). To the best of our knowledge, the first study to explore the Shannon information entropy in order to calculate the SC complexity was in 1995 (Frizelle and Woodcock, 1995). The authors considered the variety and the uncertainty in calculating the structural complexity, associated with the variety, and the operational complexity, associated with the uncertainty.

Our study focuses solely on the information flow. The word information derives from the Latin word “informare" which means to form or to shape an object. This etymology combines the structure and the information about an object (Sveiby, 1996). Given that the complexity is proportional to the information needed to operate an SC, and that uncertainty forces the SCM to use information, the Shannon information entropy, which measures the amount of uncertainty in a system, also measures some kind of complexity of the SC. We call it the 'informational complexity'.

## 3. THE RESEARCH

A complexity measurement should inform managers that the current complexity of an SC is $n$ in a range of [0 - $m$], and what uncertainty needs to be mitigated to achieve a certain complexity $c$. To differentiate this measurement from others, this study assumes that any variation in the financial or in the material flow will necessarily be reflected in the information flow. If the probability of requesting non-regular or unexpected information during the execution of an order is $p_i$, equation (1) provides the degree of uncertainty in the relationship and consequently the informational complexity.

Information that is always or never required does not relate to uncertainty and does not affect the calculation. The informational complexity of the entire SC is the sum of all significant complexities.

The study investigated two SCs in the footwear industry. The first supplies safety shoes for industrial workers, mainly in the mechanical and the building construction industries. The second SC supplies high-quality women's shoes to domestic retailers and foreign traders. The two SCs have relevant structural differences, so relevant differences in complexities are expected.

Footwear manufacturing requires labor-intensive SCs which usually comprise cutting, sewing, pre-fabrication, assembling, finishing, and shipping. For the cutting process suppliers, provide raw materials, molds, and razors. In the sewing process, the cut parts are joined by gluing or using sewing machines. The pre-fabrication process produces individual parts such as the outsole, midsole, insole, heel, heel cap, stiffener, quarter, tongue, or toe cap. In the assembling process, the individual parts are mounted on the mold and joint. The finishing includes the final operations such as brushing, cleaning, and the fitting of the shoelaces and aesthetic items. Finally, the shipping comprises the final inspection, packaging, and shipping.

Our methodology consisted of: (i) a focus group with five SC managers from the footwear industry in which the participants, supported by one of the researchers, outlined the information that may be required in a typical footwear industry SC; (ii) interviews with three managers and practitioners from each SC who outlined the hardcore of the SC and calculated the probability of listed information being required during the execution of an order (practitioners collected the last ten production orders between two parts and counted in how many of them the information was necessary); (iii) calculation of the SC complexity using Equation 1 and $n = 2$ (information required or not); and (iv) a comparison of the uncertainties that needed to be mitigated to control the complexity.

### 3.1. The SC Complexity Calculation

Five experienced SC managers from the footwear industry with an educational background (engineering and MBA or MSc level) made up the focus group. With the mediation of a researcher experienced in the industry, the group listed the information exchanged between companies in the execution of footwear manufacturing orders. Using discourse analysis, researchers structured the information. Finally, the structured information was reviewed and refined in line with the managers' feedback. Table 1 shows the structure.

**Table 1 – Structure of information in the SCM**

| Issue | Tag | Information |
|---|---|---|
| Planning and scheduling | I1 | Forecasting |
| | I2 | Manufacturing capacity |
| | I3 | Scheduled maintenance |
| | I4 | Leadtimes and deadlines |
| Logistics | I5 | Scheduled shipments |
| | I6 | Scheduled arrivals |
| | I7 | Shared inventory situation |
| | I8 | Shared transportation situation |
| Labor | I9 | Availability of skilled operators |
| | I10 | Availability of skilled designers |
| Finance | I11 | Cash-Flow |
| | I12 | Shared purchases |
| | I13 | Credit, payments, and loans |
| | I14 | Shared Financing |
| Technology and innovation | I15 | Product development |
| | I16 | Process development |
| | I17 | Shared investments |
| | I18 | Shared machine |
| | I19 | Technology transfer |
| | I20 | Technical support |

Due to the phenomenology present in the research, the said framework is only valid for the footwear industry, at the time period of the research, and from the perspective of the participants. Another industry, another time period, or other participants could produce a slightly different structure.

To adjust production planning, the SCM may require members to provide forecasting, installed capacity, planned maintenance, and typical lead times and deadlines. To manage the logistics operations, the SCM may need to request forecasts for deliveries, consignments, and about the inventory situation and a forecast of shareable transportation, especially the use of milk-run transports. For labor, SCM may require specialized operators or qualified designers for differentiated orders. For finance, it may be necessary to know about the cash flow, the possibility of sharing purchases and financing, and to grant credits, advances, or loans for the execution of orders. Finally, in terms of technology, the SCM may need information on product and process developments, investments and shared equipment, technology transfer, and technical assistance.

## 4. TWO CASES

The first case regards a safety shoe SC. The product is a commodity with few innovations which has to comply with safety standards. Consumption does not vary from season to season, and production lots are large. There is no need for specialized operators and the required level of manufacturing technology is intermediate. The SC supplies institutional customers (usually building and heavy construction companies) and retailers that sell to individuals or small companies. The two distributors have a joint inventory policy which prevents shortages. The main strategic priorities of the SC are cost reduction and quality improvement.

Figure 1 represents the hardcore of the SC. Table 1 presents the probabilities of an unexpected information request during the execution of an order. The positions without an assigned probability represent unrequested or permanently available information and do not represent uncertainty and therefore do not represent complexity.

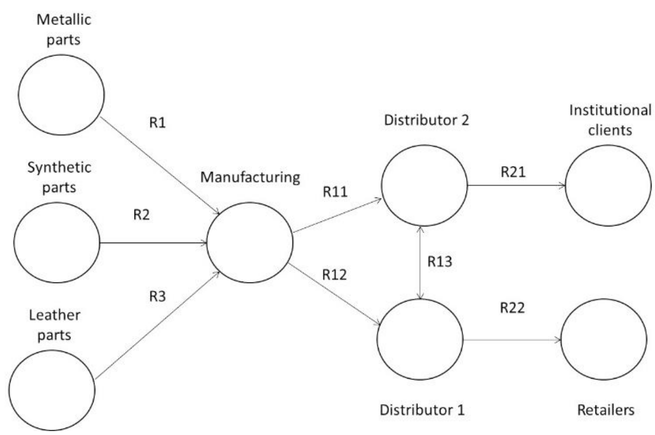


Figure 1 - The hardcore of the first SC

**Table 1 - Probabilities for the first SC**

| | R1 | R2 | R3 | R11 | R12 | R13 | R21 | R22 |
|---|---|---|---|---|---|---|---|---|
| I1 | | | | | | | 10% | 50% |
| I2 | 30% | 60% | | | | | | |
| I3 | 50% | | 60% | | | | | |
| I4 | | | | | | | 30% | 60% |
| I5 | | | | | | | | |
| I6 | | | | | | | | |
| I7 | | | | | | 10% | | |
| I8 | | | | | | 10% | | |
| I9 | | | | | | | | |
| I10 | 10% | | | | | | | |
| I11 | 20% | 10% | 40% | | | | 10% | 50% |
| I12 | | | | | | 30% | | |
| I13 | 50% | 20% | 50% | | | 30% | | |
| I14 | | | | | | 20% | | |
| I15 | 10% | 20% | | | | | | |
| I16 | 40% | 60% | | | | | | |
| I17 | | | | | | 10% | | |
| I18 | | | | | | | | |
| I19 | 20% | | | | | | | |
| I20 | 20% | 40% | | | | 10% | 10% | |

For example, in the relationship R1 (manufacturing and metallic parts supplier), the probability of an unexpected request in relation to the manufacturing capacity I2 is 30%. This means that in 3 out of 10 orders, during the execution, some unexpected occurrence forced the reallocation of the production due to machine overload. Applied to R2-I2, equation 1 ($n$ = 2) results $H(p)$ = 0.88. In R2, the problem occurred in 6 out of 10 orders, meaning that no request is the exception and the information was expected to be present in the order. To decrease the complexity, in the first case, the solution is to eliminate the need for the information. In the second case, as the need for the information is the rule, not the exception, the solution is to incorporate the information in the regular order. In both cases (0% and 100%), the uncertainty vanishes and the complexity decreases.

Applying equation (1) to the uncertain cells and summing the individual cell outcomes, results in a complexity of 24.34 units. Taken absolutely, a single complexity has little intrinsic value (Isik, 2010). A strategic analysis requires a context. Since equation (1) reaches a maximum value at $p_i$ = 0.5 (maximum uncertainty), the maximum complexity is 160 units and the relative complexity is 24.34/ 160 = 15.2%.

Previous research has provided evidence that in manufacturing the higher the complexity, the lower the performance (Bozarth et al., 2009; MacDuffie et al., 1996). To reduce the complexity, one route is to eliminate connections, which reduces the reliability of the SC. For instance, R13 ensures that one distributor will support the other in partial shortages. The second route is to accept the current structure and reduce the uncertainty in Table 1. Incorporating the information in the regular procedures of the SCM should eliminate the higher probabilities. Adopting policies to prevent the uncertainty should decrease or even eliminate the lower probabilities. When the information is always available or no longer needed, the uncertainty vanishes and the complexity decreases.

The second case comprises a women´s shoes SC. The product is high value-added, consumption is highly seasonal, production requires small lots and artisanal workforce supplied by *ateliers* (small workshops with skilled workers, usually retired from the industry, that perform highly specialized procedures), and permanent innovation. The SC supplies domestic and foreigners traders. The main priorities of the SC are flexibility, dependability, and innovation.

The main differences from the first case are the design center and the *ateliers*. The design center helps the manufacturing to meet innovation challenges, whereas the *ateliers* help to achieve flexibility in handling the variety in the production mix, the lot sizes, fast-deliveries, and unpredicted orders. As in the first case, the presence of two distributors ensures the channels are more reliable, which itself offers guarantees to the clients. Figure 1 represents the hardcore of the SC.

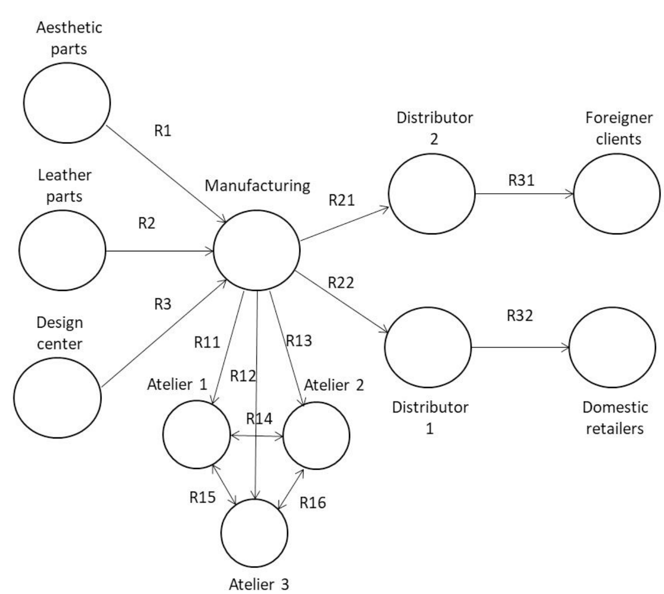


Figure 2 - The hardcore of the second SC

Table 2 presents the probabilities of unexpected information requests. Recurrent application of equation (1) results in a complexity of 72.87 units. The maximum complexity is 260 units and the relative complexity is 72.87/ 260 = 28.0%.

**Table 2 - Probabilities for the second SC**

| | R1 | R2 | R3 | R11 | R12 | R13 | |
|---|---|---|---|---|---|---|---|
| I1 | 30% | 20% | | | | | |
| I2 | 20% | 10% | | | | | |
| I3 | 20% | | | | | | |
| I4 | 40% | 20% | | 20% | 20% | 20% | |
| I5 | 20% | 10% | | 40% | 30% | 30% | |
| I6 | 10% | | | | | | |
| I7 | | | | 40% | 30% | 30% | |
| I8 | | | | 50% | 20% | 30% | |
| I9 | | | | 60% | 70% | 60% | |
| I10 | | | 60% | | | | |
| I11 | 10% | 20% | 20% | | | | |
| I12 | | | | 20% | 10% | 10% | |
| I13 | 30% | 40% | 20% | 40% | 30% | 40% | |
| I14 | | | 20% | | | | |
| I15 | | | 60% | | | | |
| I16 | 10% | | 20% | 20% | 30% | 30% | |
| I17 | | | | | | | |
| I18 | | | | | | | |
| I19 | | | 20% | | | | |
| I20 | | | 40% | 40% | 50% | 20% | |
| | R14 | R15 | R16 | R21 | R22 | R31 | R32 |
| I1 | | | | 30% | 10% | 20% | 30% |
| I2 | | | | 20% | 30% | | |
| I3 | | | | | | | |
| I4 | | | | 30% | 50% | 10% | 30% |
| I5 | | | | 20% | 30% | 20% | 40% |
| I6 | | | | 20% | 40% | 10% | 30% |
| I7 | 20% | 20% | 20% | | | | |
| I8 | 30% | 30% | 30% | | | | |
| I9 | 20% | 30% | 30% | | | | |
| I10 | | | | | | | |
| I11 | | | | 20% | 40% | | 40% |
| I12 | | | | | | | |
| I13 | | | | 10% | 50% | 20% | 40% |
| I14 | | | | | | | |
| I15 | | | | | | 20% | |
| I16 | | | | | | | |
| I17 | | | | | | | |
| I18 | 20% | | 30% | | | | |
| I19 | | | | | | | |
| I20 | 10% | 20% | | 20% | 30% | 30% | |

The relative complexity in the second SC is greater than in the first SC. The main reason stems from the strategic priorities, cost and quality in the first SC, flexibility, dependability, and innovation in the second. In the first SC, reducing complexity helped to reduce cost and improve quality, in accordance with the literature (Bozarth et al., 2009; MacDuffie et al., 1996). In the second SC, innovation and flexibility increased the relative complexity. More than half (circa 54 percentage points) is due to the design center and the network of ateliers. If both innovation and flexibility were excluded, the new relative complexity would be 12.9%, which is closer to the first SC.

## 5. CONCLUSION

This study has some key differences from other studies that have used the Shannon information entropy to measure or evaluate the SC complexity.

Frizelle and Woodcock (1995) defined the complexity of an SC as the variety and uncertainty present in the system. On the other hand, our study considers that some kinds of SCM can control the variety without producing uncertainty. When variety implies uncertainty, an unexpected request for information may mitigate it. Therefore, it is not necessary to control variety by itself, but rather to control for non-regular information that mitigates the effect of variety.

Modrak and Bednar (2016) consider three flows as sources of complexity, materials, financial, and information. Our study, on the other hand, considers that both materials and financial uncertainty are reflected in an unexpected request for information. Therefore, by capturing the information flow, the three complexity sources are also captured.

Isik (2010) states that an isolated measurement of complexity has no value on its own. Our study provides the basis for comparison, the maximum possible complexity of an SC. Our study also differentiates between the part of the complexity that stems from cost and quality priorities and the part that stems from flexibility, dependability, and innovation. Isik (2010) recognized that reducing the complexity might reduce profits if the competition requires flexibility. Serdarasan (2013) states that only the unnecessary complexity should be eliminated. Our study states that the sources of complexity or complexity drivers that lead to the achievement of a priority should be managed, not eliminated.

Finally, Kriheli and Levner (2018) consider that the SC complexity stems from the nodes of a graph. Our study considers that complexity stems from the edges.

This study poses challenges for further research.

The first challenge is to establish a relationship between complexity and performance. At least two studies (Carbonara, 2016 and Sellitto et al., 2018) have highlighted that this relationship is non-linear. The first study approached four Italian industrial districts, in which those with very low and very high numbers of mutual relationships have lower performance than the intermediate group. The second study approached a short food supply chain (SFSC) that expanded its radius of operations to gain scale. The study showed that up to 12 kilometers, the scale improved the performance. However, from 12 kilometers upwards, increasing coordination losses decreased profits. Both studies suggest a nonlinear relationship between complexity and performance.

The second challenge is to associate the complexity with the strategic priorities of the SC. Our study shows that when the priorities differ sharply, the complexity also differs substantially. Further studies should explore the non-linearity as well as the relationship between complexity and priorities.

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