ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

MODELING AND ANALYSIS OF GLOBAL SUPPLY CHAIN DISRUPTION BASED ON PETRI NET

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Abstract. *In a context of increasing competition, rising of expectation for product innovations, and need to satisfy different consumer needs, the concept of global supply chain management (GSCM) emerges as a strategy to more efficiently coordinate the geographically dispersed activities of production systems that generally involve several manufacturing processes. However, adopting GSCM, organizations have to deal with external risks that impact the manufacturing and distribution management of final products or services from supplier to final customer, such as transport interruption, power supply failure, natural disasters and terrorist attacks. The paper approach considers a method for modeling supply chains as a discrete event system and simulation analysis of GSCM activities based on formal techniques, such as Petri net (PN). This approach also considers a discussion about disruptions in global supply chains and the advantages of adopting a mathematical model.*

Keywords: *Dispersed production system, PN – Petri net, GSCM – global supply chain management, discrete event system, manufacturing system, supply chain disruption*

1. INTRODUCTION

The occurrence of an expected event can be seen in three ways: (1) when an event is expected, but does not happen; (2) when an event that is not expected, but thinkable, happens; and (3) when an event that is not expected and not thinkable, happens (Weick and Sutcliffe, 2007). In this scenario, we have manufacturing systems and global supply chains that cross boundaries and spread their operations globally, attracting more and more attention to external events exposure and impacts on global operations.

At this point, it is important to define two types of events in supply chains: disturbances and disruptions. Both include low service performance, inventory accumulation, unexpected costs, profit constraints and market share reduction. The difference lies in post-disruption impacts. Disturbances involve connected supply chain actors adapting to variations in material or information flow, and the chain structure does not change as a result of the adaptation process (Weick and Sutcliffe, 2007; Greening and Rutherford, 2011). Examples are: demand fluctuation, material and service supply fluctuation, temporary capacity constraints, temporary quality problems of parts, isolate and transitory strategies among supply chain actors, unplanned incidents that temporarily impact goals shared by supply chain actors (Sheffi and Rice, 2005; Bolstorff and Rosenbaum, 2012). In contrast, disruptions involve the removal of ties from the chain (either permanently or temporarily) as a consequence of some unanticipated critical event; the post-disruption chain structure is irreversibly different from the pre-disruption chain and the adaptation process inevitably involves the residual existing actors renegotiating and in some cases establishing new relationships (Greening and Rutherford, 2011). Examples are: transport interruption, power supply failure, port operation halt, natural disasters (such as flooding, earthquake, and typhoon) and human issues (such as terrorist attacks, and political instability) (Sheffi and Rice, 2005; Funabashi and Takenaka, 2011; Vakharia and Yenipazarli, 2009; Kim *et al*., 2004; Lu *et al.*, 2011; Lam and Yip, 2012). Despite several studies focused on these aspects, it is difficult to find works about analysis systematization on disruption events in supply chains. Therefore, the present paper is about disruption impacts in manufacturing systems and in global supply chains.

Here, productive systems are defined as a plant or a production unit which process physical or information items for goods or service production (Villani *et al.*, 2007). Among the types of productive system there are manufacturing systems, the main characteristic of which is the physical creation of something, in other words, output consists of goods that physically differ in shape, content, etc., from input materials, such as coalmine, construction and factory process (Wild, 1977; Garcia Melo *et al.*, 2010a).

Considering the globalization of economy, competition is no longer considered the only relationship that maximizes company profits, emerging as a new paradigm; collaboration, which consists in the direct participation of two or more actors in the project, in production or marketing and generally involves vertical internal arranges among company areas or along supply chain (Polenske, 2004). In this context, global supply chains can be understood as dispersed

ISSN 2176-5480

manufacturing systems, i.e., plants of productive systems geographically dispersed. In these chains, collaborative relation is based on a dyad formation between suppliers and clients (Greening and Rutherford, 2011) in which communications normally deal with a large amount of information among productive centers of an entity (company or a type of consortium), but in different geographic locations (Miyagi *et al.*, 2009). Here, a geographic location means continents, countries, cities, etc. (Garcia Melo *et al.*, 2010a).

Among the practices to mitigate disruptions, Weick and Sutcliffe (2007) propose that supply chains have to be resilient as a way of mitigating disruptions and as a company ability to maintain or to recover the stable dynamic state to continue operating faced with a mishap or in the presence of a constant stress (Hollnagel, 2007 *apud* Weick and Sutcliffe, 2007). The concept of Global Supply Chain Management (GSCM) arises, originally created to coordinate activities more effectively in global supply chains (Cohen and Mallik, 1997) and is adapted to deal with disruptions started by unexpected events.

In this way, a global supply chain modeling method is presented to analyze impacts of a disruption in chains operations and the adoption of GSCM practices to recover the chain. This approach considers manufacturing systems and global supply chains as discrete event systems (Villani *et al.*, 2007; Miyagi *et al.*, 2009; Lu *et al.*, 2011), and Petri net as graphical modeling and a mathematical technique for analysis and design (Adam *et al.*, 1998; Nassar *et al.*, 2008; Riascos and Miyagi, 2010).

This paper has four other sections. Section 2 presents the literature review and fundaments. Section 3 introduces a modeling and analysis method and its stages description. Section 4 illustrates the method with an application example. Finally, section 5 concludes the paper with a discussion about the advantages of the method proposed.

2. FUNDAMENTS AND LITERATURE REVIEW

2.1 Manufacturing System and Global Supply Chain Disruption

A global supply chain is based on collaborative supplier-client relationship (dyad) among dispersed manufacturing systems that compose a chain. GSCM is defined as a coordination strategy of all collaborative activities of these manufacturing systems (in the role of suppliers, producers or clients) that aims to produce or to deliver the right number of items (material and information), in the right place, at the right time, minimizing the supply chain global costs and maximizing its service levels (Tuncel and Alpan, 2010). Additionally, there is a GSCM trend to include mitigation and disruption recovery. This trend is motivated by: (1) demand for a lean supply chain which increases companies interdependency in the global chain; (2) generalized business globalization that increases disruption risks related to this structure; (3) current practices of business continuity planning that is insufficient to mitigate disruption impacts; (4) specific regulation in each community and (5) consumer innovations that also characterize the non-financial impacts of the disruptions (Vakharia and Yenipazarli, 2009).

The literature shows that GSCM for disruption cases has become an attractive field for researchers as, for example, in 1999, Floyd hurricane flooded the Daimler-Chrysler plant located in Greenville city (United States), responsible for automotive components, resulting in production halt of all related North American plants for seven days (Kim *et al.*, 2004). In 2011, a terrorist attack made American government close borders, halt air transport and inactivate Ford Motor Co. lines due to component supplier disruption from Canada and Mexico (Sheffi and Rice, 2005). More recently, an earthquake and a tsunami in the northeast area of Japan impacted three Toyota factories and forced the company to halt its production not only in Japan but in many other countries for several weeks. In a press conference, Toyota's president Akio Toyoda attested that "since Toyota depends so much on domestic part suppliers, any major disruption in supply chains could cripple its outputs" (USA Today, 2011).

According to Weick and Sutcliffe (2007) the system resilience indicates how flexibly manufacturing systems and global supply chains can operate without disruption, and how efficient the adopted mitigation and recovery practices are. Sheffi and Rice (2005) indicate that the company performance and disruption recovery process can be defined in eight stages (Fig. 1): (1) preparation, (2) disruptive event, (3) first response, (4) initial impact, (5) time of full impact, (6) preparation for recovery, (7) recovery, (8) long-term impact. The performance here is defined by sales, stock levels, profits and client service.

In sum, stages are defined by Sheffi and Rice (2005) as follows: (1) a company can foresee and to prepare for disruption, minimizing its effects (in some cases, such as natural disasters and terrorist attacks, there is little or no warning); (2) disruption event happens; (3) first response focused on controlling the situation, saving or protecting lives, shutting down affected systems and preventing damage; (4) the full impact of disruption is felt immediately; (5) performance drops significantly; (6) preparation for recovery typically starts in parallel, involving qualifying other suppliers and alternative transportation modes; (7) to get back to normal operation levels, many companies run at higher-than-normal utilization level, using overtime as well as suppliers' and customers' resources; then (8) permanent impacts are noticed after disruption. Considering Sheffi and Rice proposal (2005), it is crucial to systematize the modeling and analysis process of a supply chain before disruption, the impact during disruption, and the recovery process; in other words, stages 1, 2, 3, 4, 5, 6 and 7, in which the performance must consider aspects of production level (such as the number of items produced).

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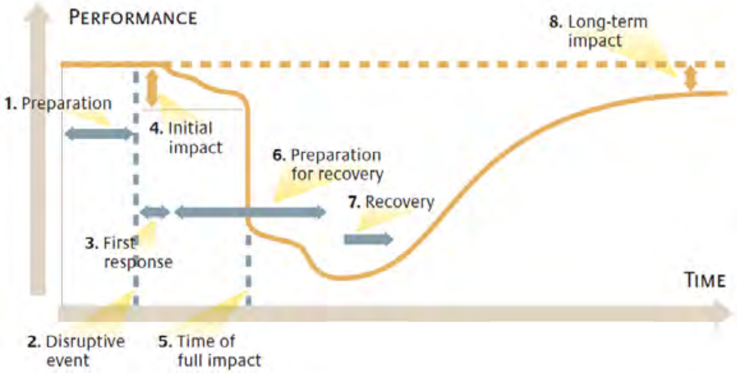

Figure 1. Disruption Profile (Sheffi and Rice, 2005).

For disruption mitigation practices, the literature suggests a GSCM strategy that should consider: (1) monitoring little damages and treating them as a symptom that something is going wrong in the chain; (2) resistance against simplification (local solutions without considering side effects); (3) acquired know-how of past events; (4) redundancies; (5) operation flexibility; (6) partnership creation for knowledge transference in case a disruption occurs (Weick and Sutcliffe, 2007; Sheffi and Rice, 2005; Lam and Yip, 2012).

Considering the current scenario, in which there are constant disruption risks in supply chains, impacts complexity, need of a formal analysis tool and methodology in related areas, we understand that the discrete event system approach and the Petri net technique can be explored as a GSCM modeling and evaluation practice.

2.2 Discrete Event System and Petri Net

The literature presents different system classifications (Cassandras and Lafortune, 2008; Chung, 2004; Miyagi, 1996) in which discrete dynamic event systems (DDES or DES) consist in states that change in a discrete way as events occurs. In this context, Villani *et al*. (2007) add, manufacturing systems behave according to rules and proceedings defined by man (also called *man-made systems*) and they are generally classified as DES. Therefore, supply chains can also be treated as a DES (Lu *et al.*, 2011; Lam and Yip, 2012; Tuncel and Alpan, 2010).

Created by Carl Adam Petri in 1962, Petri net is a graphical and mathematical tool for modeling, formal analysis and design of DES (Adam *et al.*, 1998; Nassar *et al.*, 2008). Petri net is described by a 4-tuple: $PN = (P; T; F; M)$ where: P is a set of passive elements called places (in this text, the specific terms related to Petri net are in Arial type), T is a set of active elements called transitions, F is a set of relations between passive elements and active elements called oriented arcs, and M is a vector called marking. P and T are finite sets, nonnegative ($P \cup T \neq \emptyset$) and disjoint sets ($P \cap T = \emptyset$). Arcs always connect different types of elements, i.e., $F \subseteq (P \times T) \cup (T \times P)$ and M is a vector of integer nonnegative numbers in which each element mi indicates the number of tokens (marks) in place pi , i.e., $mi = M(pi)$. Petri net adopts a graphical representation for the relationship among elements and its definition also involves transition "firing" rules. The firing of a transition t in marking M is indicated by $M[t>M'$ where, M' is a resulting marking. One of the main characteristics of Petri nets is property identification and verification of precedence relations between events, concurrent operations, appropriate synchronization, deadlock conditions, repetitive activities and mutual exclusion of shared resources (Murata, 1989; Zurawski and Zhou, 1994).

Based on the Petri net modeling power, many extensions have been developed for practical applications such as supply chains. Wu and Blackhurst (2004) adopted a Petri net extension with costs and time indexed to places and transitions and proposed a methodology based on hierarchical levels to evaluate the system performance and to analyze chain disruptions. The approach to synthesize and to analyze the chain is composed of three parts: (1) *single system module*, (2) *synthesizing module*, (3) *system analysis module*. Tuncel and Alpan (2010) adopted stochastic Petri net and proposed a framework to model a supply chain and to analyze the impact of different risks. They proposed the construction of a FMECA (Failure Mode Effects and Criticality Analysis) table to map and to prioritize risks, then, included prioritized risks in Petri net and used probabilistic condition in transition firings to represent the exposure against different risk levels. Lam and Yip (2012) also developed a stochastic Petri net model to study the dynamic behavior of a supply chain. The method adopted first translates the supply chain into a Petri net and then develops risk factors in the model.

As Cassandras and Lafortune (2008) indicated, different Petri net extensions have been developed and are under continued study, allowing representation and management of more complex systems (Garcia Melo *et al.*, 2010a; Junqueira and Miyagi, 2009; Nakamoto *et al.*, 2009; Riascos and Miyagi, 2010). Studies confirm the advantage of considering manufacturing systems and supply chain as DES and the use of Petri nets to model, to visualize dynamic behavior and operation analysis. Although some proposals include disruption modeling, we notice a gap in the literature

ISSN 2176-5480

review regarding global supply chains recovery after a disruption event. Specially the absence of a systematic procedure for modeling and for analyzing the manufacturing system and the global supply chain, including disruption evaluation and supply chain recovery.

At conceptual level, a global supply chain must be understood as a whole system and the model derived can be refined through a *top-down* approach. Then a Petri net derived technique named PFS (*Production Flow Schema*) is considered for this conceptual view. The system is interpreted as a DES and therefore it is characterized by items flow (material or information flow) and productive process. The PFS has three basic elements (Miyagi, 1996): (a) active element (activities); (b) passive elements (distributors) and (c) arc (defined by components relations). Manufacturing system modeling using PFS for a top-down approach allows a smooth conversion from a conceptual model to a formal and functional detailed model (as Petri net), as presented in Fattori *et al*. (2011) and Garcia Melo *et al*. (2010b). This is named PFS/Petri net technique (Miyagi, 1996).

3. MODELING AND ANALYSIS METHOD

The objective of the modeling and analysis method is to obtain a structural and behavior representation of a supply chain, to the evaluation of a supply chain after a disruption in the manufacturing system, and to verify the recovery process with GSCM practices. The method proposed explores the general idea presented in Garcia Melo *et al*. (2010b) but focuses on the global supply chain issues. This method is composed of four stages:

- *Stage 1: Global supply chain and manufacturing system scopes* – At this stage, functional characteristics of global supply chain and manufacturing systems are identified and documented in an informal way. Dyads from supply chains are defined at this stage. After establishing functional characteristics, simulation scenarios are also evaluated. The scenario A is the global supply chain operating in normal conditions and scenario B is when global supply chain impacted by a disruption event. After detecting disruption, a recovery action based on a GSCM practice is assumed to establish chain operation. The disruption event, its impacts and recovery action are defined. Premises and simplifications should be listed to define model representation limits.
- *Stage 2: Conceptual and functional modeling of manufacturing systems and supply chains* – Initially, each manufacturing system and the supply chains are represented by a conceptual model; then, a conversion to functional models is performed following PFS/Petri net technique.
- *Stage 3: Model verification and validation* – At this stage, the derived Petri net models are verified and validated. The models are submitted to a dynamic behavior and structural analysis. These analyses are based on the identification of structural properties and the evaluation of graph behavior (deadlocks, dynamic instability and undesirable states). Simulation technique is used to confirm the model expected behavior.
- *Stage 4: Information collection about the supply chain performance* – Finally, performance metrics and premises are defined to the scenarios and/or situations to be studied. The parameters of the simulation to be conducted (for example, initial marking, number of transition firing, number of simulations) are chosen. Experiments are then performed and information data are collected to evaluate the GSCM.

4. APPLICATION EXAMPLE

An application example of the method proposed considers a global supply chain in Fig. 2.

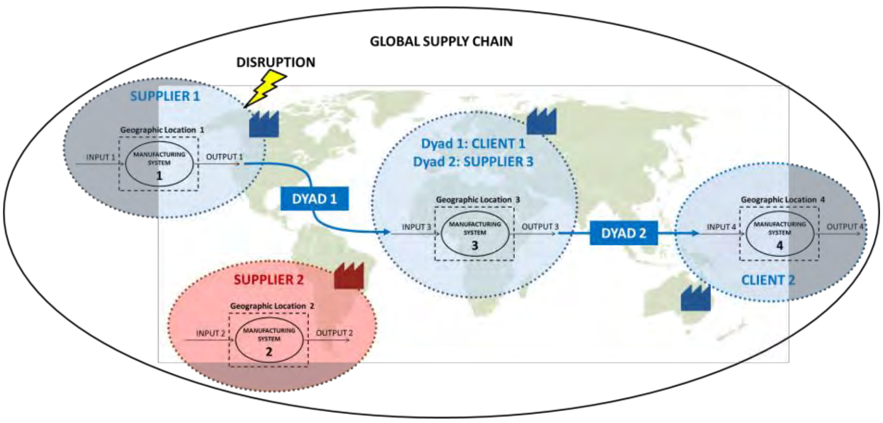

Figure 2. Global Supply Chain Structure.

Stage 1: Global supply chain and manufacturing system scopes – This global supply chain is considered to be composed of three manufacturing systems. “Dyad 1” is formed by “Manufacturing System 1”, responsible for material supply (“supplier 1” in “dyad 1”) to its client “Manufacturing System 3” (“client 1” in “dyad 1”). Another supplier-

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client relationship is verified in the chain: "Dyad 2", in which "Manufacturing System 3", previously a client in "dyad 1", assumes the role of material supplier ("supplier 3", in "dyad 2") to its client "Manufacturing System 4" ("client 2"). In this example, "Manufacturing System 1", "Manufacturing System 2", "Manufacturing System 3" and "Manufacturing System 4" are geographically dispersed, in geographical locations 1, 2, 3 and 4, respectively.

In scenario A, "Manufacturing System 2" does participate in the global supply chain, but its process and products (type and quality) are similar to "Manufacturing System 1" process and can then be a material supply option to "Manufacturing System 3".

In scenario B, a disruption event is considered in geographical location 1. As a premise, this event causes operation disruptions in "Manufacturing System 1", immediately blocking material supply to its client, "Manufacturing System 3", that will notice this halt.

Literature alerts that the manufacturing system can be impacted by critical parts supply halt if its operations depend on a single supplier and suggest that GSCM should allow a supply chain recovery process by renegotiating its ties urgently with other actors (Sheffi and Rice, 2005). In this case, Greening and Rutherford (2011) reinforce a difference in this new tie: the authors affirm that, in normal situations, companies make rational choices related to market and partnerships, and that the initial point to create a new collaborative relationship is motivated by a competitive advantage, followed by creating a tie with other actors in the supply chain, a new coordination process and productive systems alignment to a single goal. In contrast to this motivation, in case of a supply chain disruption, the initial point to create a new relationship is process alignment and pre-disruptive performance recovery.

Thus, after detecting a lack of supply, "Manufacturing System 3" based on a GSCM practice, may look for new suppliers to establish a new relationship that could replace "dyad 1". In this case of supply chain recovery, "Manufacturing System 2" can assume the material supply ("supplier 2") to "Manufacturing System 3" and the chain operation is established.

This example assumes that: (1) item flow is focused on material flow, not including information and financial flow of the supply chain; (2) the consequence of a disruption is that the manufacturing system affected stops its operations immediately and suspends material supply to its client (the manufacturing system client, defined by the dyad supplier-client, in a global supply chain); and (3) the supply chain recovery procedure looks for new suppliers and the establishment of new dyads in the global supply chain as a GSCM practice for disruption recovery.

Stage 2: Conceptual and functional modeling of manufacturing systems and supply chains – A conceptual model in PFS of the manufacturing systems (MS) and of supply chains is created and then the model is refined in a top-down approach (Fig. 3 and 4). The resulting functional model in Petri net is shown in Fig. 5. The software HPSim (HPSim, 2003) was used to model edition. Table 1 presents the interpretations of transitions and places of the Petri net model in Fig. 5. Note that this model considers scenario A and scenario B: if P_SM1_HAB is enabled, it means that Manufacturing System 1 is working as supplier, and if P_SM2_HAB is enabled, it means that Manufacturing System 2 is working as supplier because there was a disruption event in Manufacturing System 1.

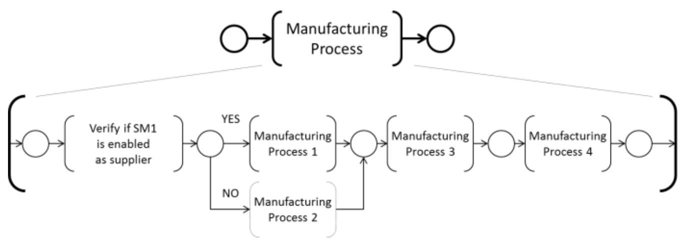

Figure 3. PFS model of [Manufacturing Process] function.

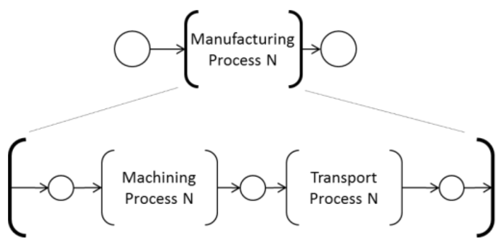

Figure 4. Refinement of PFS model.

ISSN 2176-5480

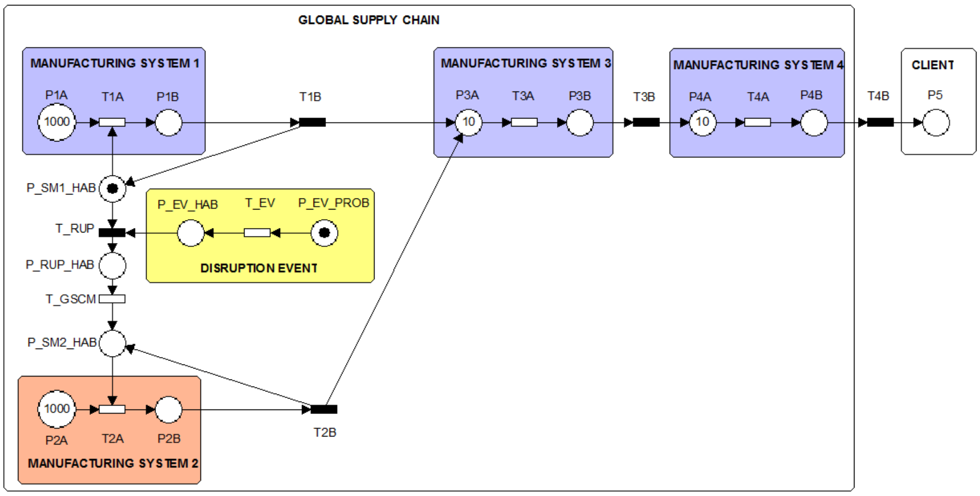

Figure 5. Functional model in Petri net (software HPSim printscreen).

Table 1. Interpretation of transitions and places of the Petri net in Fig. 5.

Name	Type	Description
P1A	Place	Material available to machining in Manufacturing System 1.
T1A	Transition	Machining process in Manufacturing System 1.
P1B	Place	Machined material and available to transport in Manufacturing System 1.
T1B	Transition	Material transport process from Manufacturing System 1 to 3.
P2A	Place	Material available to machining in Manufacturing System 2.
T2A	Transition	Machining process in Manufacturing System 2.
P2B	Place	Machined material and available to transport in Manufacturing System 2.
T2B	Transition	Material transport process from Manufacturing System 2 to 3.
P3A	Place	Material available to machining in Manufacturing System 3.
T3A	Transition	Machining process in Manufacturing System 3.
P3B	Place	Machined material and available to transport in Manufacturing System 3.
T3B	Transition	Material transport process from Manufacturing System 3 to 4.
P4A	Place	Material available to machining in Manufacturing System 4.
T4A	Transition	Machining process in Manufacturing System 4.
P4B	Place	Machined material and available to transport in Manufacturing System 4.
T4B	Transition	Material transport process from Manufacturing System 4 to final client.
P_EV_PROB	Place	Marking with 1 token indicates that the model considers a disruption.
T_EV	Transition	Event occurs in geographical location 1.
P_EV_HAB	Place	This place enables the impact of a chain due to a disruption.
P_SM1_HAB	Place	Manufacturing system 1 is enabled as a supplier to 3.
T_RUP	Transition	Disruption event impact on Manufacturing System 1 and its operations
P_RUP_HAB	Place	Chain is impacted and material supply to Manufacturing System 3 is interrupted, indicating the need for a recovery.
T_GSCM	Transition	A new supplier is enabled and a new dyad is planned as a GSCM action.
P_SM2_HAB	Place	Manufacturing System 2 is enabled as a supplier to 3

Stage 3: Model verification and validation – At this stage, the Petri net model is verified and validated based on the state space diagram, in which possible states of the system from an initial marking is observed. The verification of structural properties was conducted with HPSim software, but due to some tools available, the software PIPE2 (PIPE2, 2009) was used to generate the state space diagram and to verify whether undesirable states were absent. To simulate and to validate the dynamic behavior of the Petri net model, both types of software (HPSim and PIPE2) were used.

Stage 4: Information collection about the supply chain performance – In this case, the parameters adopted are: the increment in time simulation evolution (sample time) is 1ms, the maximum number of steps is 100.000, and the maximum simulation time is 1000ms. Simulation experiments duration is limited by time, and in the initial situation, Petri net marking P1A and P2A places have 1000 tokens, minimizing supply halt risk in "Manufacturing System 1" and "Manufacturing System 2", and P3A and P4A places have 10 tokens each, indicating intermediate stocks in "Manufacturing System 3" and "Manufacturing System 4". For simulation purposes, transitions T1A, T2A, T3A e T4A are

ISSN 2176-5480

deterministic temporal transitions. A time of 2ms (initial delay) was associated to these four transitions; hence, if one of these transitions is enabled to fire, it needs to wait for this time interval before transition firing. This delay is the time dedicated to materials machining.

Scenario A and B were defined through specific initial marking. Place P_EV_PROB with no token means scenario A will be simulated; in other words, a case without supply chain disruption. In scenario B, transition T_EV indicates an event disruption through a temporal transition associated to 50ms. This interval allows a normal operation in chain evolution and an impact analysis of the system performance. After the disruption event, a temporal transition T_GSCM with associated time of 200ms indicates GSCM action to recover “Manufacturing System 3” supply. During the system simulation, in case of disruption, the supply chain maintains production and delivery to the end client for a limited period until intermediate stocks (in P3A and P4A) are empty.

After 100ms of simulation, the performance metrics considered were stock levels in manufacturing systems and chain productivity (based on material quantity delivered to end client). Table 2 summarizes the information from simulations.

Data analysis suggests that, in scenario B, the supply chain consumes intermediate stocks, and thus, stocks are a safety practice in a supply disruption case in manufacturing systems. A productivity decrease is observed. In parallel, markings were mapped in each transition firing (tool available in software HPSim) and the graph in Fig. 6 is derived to understand the supply chain behavior before disruption, supply chain impact after disruption and the recovery of the manufacturing system.

Table 2. Simulation data

Scenario	Description	Stock in MS 1	Stock in MS 2	Stock in MS 3	Stock in MS 4	Material quantity delivered to end client	Supply chain productivity
		P1A	P2A	P3A	P4A	P5	
Today	-	1000 items	1000 items	10 items	10 items	-	-
A	Without disruption	501 items	1000 items	9 items	10 items	500 items	0,500 items/ms
B	With Disruption	975 items	625 items	1 items	1 items	418 items	0,418 items/ms

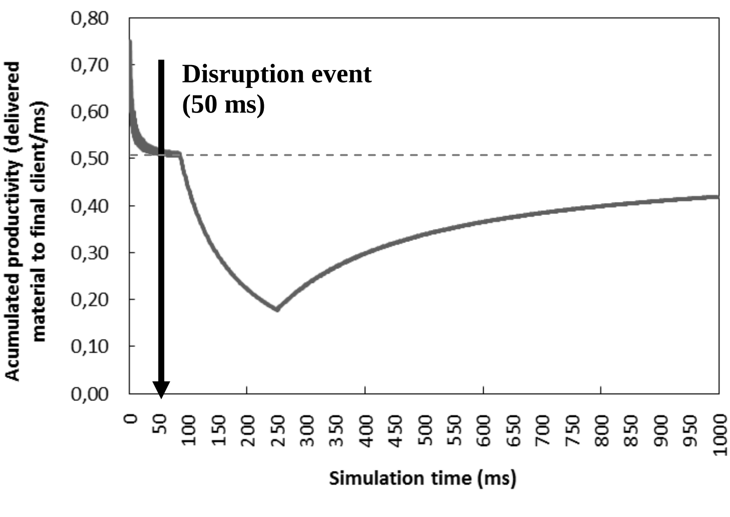

Figure 6. Accumulated productivity during simulation of the Petri net model.

5. CONCLUSION

This paper introduced a systematic procedure for modeling and analyzing a global supply chain and its respective GSCM. Based on the resulting simulation data, that is, the dynamic behavior of the system modeled, intermediate stock levels analysis in supply chain, and cause-effect relationship identified in unexpected events, we confirm that it is appropriate to consider manufacturing systems as discrete event systems and to use Petri net as a formal technique for modeling and analysis. Additionally, the PFS/Petri net technique also allows better understanding and organization to develop a functional model.

The case studies conducted confirm that simulation results derived from the application of the method proposed presents a similar disruption profile obtained by Sheffi and Rice (2005). After the disruption event, system´s performance decrease and its recovery began before enabling a new supplier in the supply chain. Experiments also confirm that chain performance, in the short term are below to the system before disruption, but indicate a reestablishment of the original performance in the long term. These statements are possible based on Petri net properties. Using a Petri net model, places can be interpreted as intermediate stocks, marks as material items and productivity (performance measure) can be calculated during marking evolution.

The method proposed has potential to generate knowledge about manufacturing systems in supply chains, disruption impacts, reestablishment of dyads, and to improve discussions about a new supplier-client relationship for recovery actions. In future works, other study cases with a larger number of systems, different disruption events, situations with more disruptions and inclusion of other mitigation and recovery actions in response to disruptions are being also considered. Another trend that can be included is a lean approach to global supply chain models.

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