STOCK-AND-FLOW SIMULATION MODELING FOR ASSESSING BASIC SUPPLY CHAIN OPERATIONS

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ABSTRACT

The supply chain is the backbone of business operations, an indispensable part of every organization, whether small or large. Effective supply chain management (SCM) is one of the most important aspects of running a successful and profitable business, leading to maximizing customer value and achieving a sustainable competitive advantage over competitors. In the era of omnipresent digitalization, SCM is subject to intensive ICT support that profoundly transforms supply chain operations. The paper aims to propose a basic simulation modeling framework suitable for carrying out various analyses *vis-à-vis* supply chain operations, based on the utilization of continuous stock-and-flow simulations. The resulting simulation model allows one to run various scenarios, making a plethora of 'what-if' analyses regarding many adjustable input variables. As an example of how digital transformation affects traditional supply chains, it provides a solid basis for further enhancements and the inclusion of additional input and output parameters for forecasting purposes.

Keywords: supply chain, modeling, stock-and-flow simulation, web-based simulation, InsightMaker®

1. INTRODUCTION

According to the process view, a supply chain represents a sequence of processes (e.g. decision-making, execution) and flows (e.g. material, information, money) that aims "to meet final customer requirements and take place within and between different supply chain stages" (Van der Vorst, 2004, p. 2). Besides the manufacturer and its suppliers, supply chains may also include transporters, warehouses, retailers, and consumers, depending on logistics flows. It includes, but is not limited to, new product development, marketing, operations, distribution, finance, and customer service (Chopra & Meindl, 2012). A generic supply chain within the context of the total supply chain network is depicted in Figure 1. Each firm (e.g. manufacturer) belongs to at least one supply chain, i.e. it usually has multiple suppliers, distributors, retailers, and consumers.

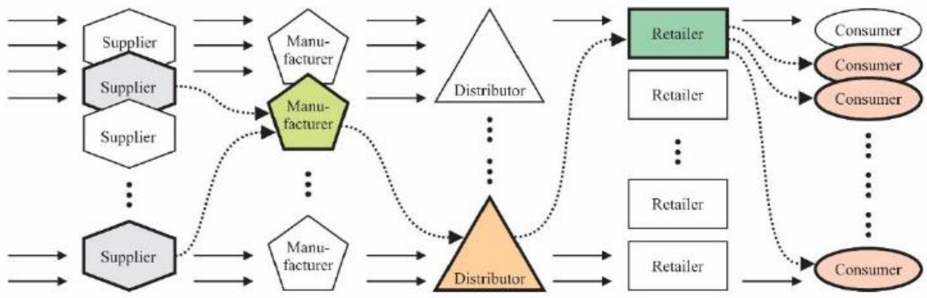

Figure 1. Schematic representation of a single supply chain (represented with dotted lines) within a total supply chain network

On the other hand, supply chain management (SCM) is "the active management of supply chain activities to maximize customer value and achieve sustainable competitive advantage. It represents a conscious effort by the supply chain firms to develop and run supply chains in the most effective & efficient ways possible" (NCSU, 2017).

In today's globalized markets, efficiently managing the entire supply chain becomes a key factor that underpins the success of businesses. In contemporary highly competitive markets, each actor in a given supply chain copes with the challenges of reducing time deadlines, inventory costs, transportation costs, and resource consumption to a minimum on all levels. However, due to the conflicts/inconsistencies that exist among particular organization objectives, their decision-making processes, non-integration of their vital processes, and poor relationships/synchronization with other actors belonging to the same supply chain, a Bullwhip effect can easily emerge with an unpredictable and devastating impact on the whole supply chain. Since computer simulation permits an evaluation of the operating performance before the execution of a given plan, the development of simulation models for supply chain management has become a necessity (Chang & Makatsoris, 2001).

Having minded the previous definitions, the paper aims to propose a stock-and-flow simulation model that would capture the basic supply chain operations among the last three actors depicted in Figure 1 (i.e. the consumers of a single retailer and one of its distributors), based on the principles of the system dynamics approach.

The rest of the paper is organized as follows. Section 2 briefly presents a literature review related to computer simulation of supply chains and the application of the system dynamics approach in building simulation models of supply chains, in the last decade. Section 3 elaborates on the common supply chain simulation approaches and focuses on the details of system dynamics. Section 4 describes the problem to be dealt with by describing the underlying causal loop diagram and formulating the corresponding SD model implemented in InsightMaker®. Section 5 evaluates the results obtained. Finally, Section 6 provides conclusions, research limitations, and future research lines.

2. RELATED RESEARCH

Due to its increased significance in recent years, computer simulation of supply chains has been put in the focus of methodologies for their analysis and assessment. The research being made in this area and being covered in this section can be roughly divided into two subcategories: (a) papers dealing with the application of computer simulation in SCM (in general) and (b) papers focused solely on the application of the system dynamics (SD) approach in modeling and simulation of supply chains. What follows is a brief overview of some of the research endeavors done in this field during the last decade.

The subsequent three pieces of research belong to the first subcategory:

Hossain & Ouzrout (2012) attempted to model trust in SCM by using Agent Modeling Language (AML) and proposing a Multi-Agent System (MAS) SCM model of trust in supply chain management. The proposed model is implemented using the Java Agent Development Environment (JADE) and the simulation results demonstrated the impact of trust in the supply chain along with the evolution of trust.

Ingalls (2014) elaborates on the reasons for using simulation as an analysis methodology to evaluate supply chains, its advantages and disadvantages compared to other analysis methodologies, and points out some business scenarios where simulation can help in obtaining cost reductions that other methodologies would miss.

Sánchez-Ramírez *et al*. (2016) develop a simulation model to improve the performance of an automotive supply chain and using sensitivity analysis, they find the values that allow the supply chain to improve its order fulfillment indicator by modification of specific variables in the model such as Cycle Time, Production Adjustment Time, Delivery Time, Raw Material Inventory, and Finished Good Inventory.

What follows are some of the most prominent research that belongs to the second subcategory:

Wai & Chooi-Leng (2011) utilize the system dynamics approach and the iThink® software to better understand the supply chain system of an actual semiconductor company and to find out better solutions through experimentations with a few key variables. The results of their research revealed that a company could achieve up to a 25% reduction in inventory cost using computer simulations.

Feng (2012) used the method of system dynamics (SD) to model supply chain information sharing, to demonstrate its importance in SCM.

Mula *et al*. (2013) propose a simulation approach based on system dynamics for operational procurement and transport planning in a two-level, multi-product, and multi-period automobile supply chain. They used the Vensim® simulation tool to highlight the potential of system dynamics for supply chain simulation. The effectiveness of the proposed model was validated through the comparison of the results provided by spreadsheet-based simulation, fuzzy multi-objective programming, and system dynamics-based simulation models. The simulation results indicated a reduction in inventory cost by about 10%.

Sundarakani *et al*. (2014) analyzed the environmental implications of the rapidly growing construction industry in the UAE using the system dynamics approach. By quantitative modeling of the construction industry supply chain, which helps to measure the dynamic interaction among various factors under multiple realistic scenarios, their study provides an analytical decision framework to assess emissions of all stages applicable to the construction industry supply chain.

Hoque & Khan (2016) attempted to provide a review of the best practices and performance measuring frameworks on supply chain performance measurement to control and improve operational efficiency and effectiveness, as well as on the system dynamics modeling solely in the field of SCM. According to their research, even though the dynamic complexity of supply chains can be handled through SD modeling, articles that provide best practices for measuring supply chain performance using the SD approach are quite rare.

There are also a rising number of Ph.D. theses that focus on the application of the SD approach to supply chains in different areas, like Li (2016), who focused on risk modeling and simulation of chemical supply chains, and Botha (2017), who used SD simulation for strategic inventory management in the automotive industry of South Africa.

Ghadge *et al*. (2018) assessed the impact of additive manufacturing implementation on aircraft supply chain networks, using a system dynamics simulation approach that revealed significant and valuable insights into supply chain performance.

In their research based on the use of agro-straw as a typical agro-waste, Liu *et al*. (2018) utilize a hybrid approach, built on multi-objective optimization and system dynamics simulation, intended for optimizing the structure of straw-to-electricity supply chain and designing motivational mechanisms to enhance its sustainability.

Abidi *et al*. (2018) present a system dynamics simulation inventory management modeling for a multi-echelon multi-product pharmaceutical supply chain that aims to support selecting optimal operational service levels regarding the total inventory cost.

3. SUPPLY CHAIN SIMULATION

As one of the several methodologies available for supply chain analysis, simulation has distinct advantages and disadvantages when compared to other analysis methodologies. Since the objective of any simulation is performance evaluation, supply chain simulation enables effective strategic planning and decision-making. Customers, products, sites, and transportation modes can be defined using specific supply chain modeling constructs. Customized business logic, objects, and rules can be defined to capture the dynamics and real-world supply chain behavior. Business policies for inventory, sourcing, transportation and production processes can be modeled, as well. Applications include (a) supply chain network design; (b) demand planning; (c) production capacity planning; (d) inventory optimization; (e) transportation modeling; and (f) modeling of warehouse operations.

Some of the most prominent benefits/features of performing supply chain simulations may include (PMC, –):

- Creation of realistic supply chain models capturing system dynamics, resource constraints, and risk;
- Simulation of existing (as-is) and improved (to-be) supply chain network designs;
- Analysis of the performance metrics such as service level, cost, inventory level, and cycle time;
- Visualization of the supply chain in action;
- Evaluation of routing strategies and testing new strategies to predict actual costs and service levels;
- Optimization of supply chain performances.

It should be notified that supply chain simulations can be carried out by using common or dedicated/specialized commercially available software packages such as Arena®, AutoMod®, ExtendSim®, ProModel®, Supply Chain Guru®, Simul8®, Solvoyo®, Tecnomatix Plant Simulation®, and Witness®. In general, supply chain simulations can be also carried out by developing and running a suitable simulation model using a general-purpose programming language (e.g. Python/SimPy).

The main approaches encompass either Discrete-Event Simulation (DES) methods or continuous simulations (e.g. stock-and-flow simulations).

A discrete-event simulation (DES) models the operation of a given system as a (discrete) sequence of events in time. Each event occurs at a particular instant in time and marks a change of state in the system. Between any two consecutive events, no change in the system is assumed to occur; thus the simulation time can directly jump to the occurrence time of the next event (Robinson, 2014). Contrary to this, with continuous simulations, the system state is changed continuously over time based on a set of differential equations defining the relationships for the rates of change of state variables. In trivial cases, those systems of differential equations can be solved analytically, otherwise, they are solved numerically, by using a computer and corresponding software, either general-purpose or dedicated one (Duivesteijn, 2006; Thierry *et al*., 2008, pp. 12–13).

System Dynamics (SD) is a methodology and a mathematical modeling and simulation technique for framing, understanding, and discussing complex issues and problems. As an approach to understanding the dynamic behavior of complex systems over time and an important aspect of the systems thinking theory, SD uses internal feedback loops, time delays, as well as stocks and flows to model the entire system. Stocks and flows are the main building blocks of SD models (Ford, 1999, pp. 14–24). Contrary to Discrete-Event Simulation (DES), SD uses a quite different approach. SD is essentially deterministic by nature. It models the observed system as a series of stocks and flows, whilst state changes are continuous, resembling a motion of a fluid at a given rate, flowing through a system of reservoirs or tanks (stocks), mutually connected by pipes (flows). Stocks are variables presenting the level of accumulation. Flows go in and/or out of the stocks, thus increasing or decreasing their values at a certain rate. In essence, SD deals with the interaction of different elements of a system in time and captures the dynamic aspect by incorporating concepts such as stock, flows, feedback and delays, and thus offers an insight into the dynamic behavior of a system over time (Tang & Vijay, 2001).

Because of its great flexibility, along with its ability to combine both qualitative and quantitative aspects of the modeled system, as well as its tendency to model and simulate the dynamics of a system at a higher, yet more strategic level to gain a holistic insight into the dynamic interrelations among the different parts of a complex system, SD has been applied in many different fields of study so far, including project management, system analysis, health care, supply chain management, logistics, sustainability, environmental science, etc. The SD approach has become popular in SCM during the last two decades, although it was initially introduced by Jay Forrester in 1961.

Given the accuracy of this modeling method that permits building formal computer simulations of complex systems and their use to design more effective policies, in this paper, we revert to continuous simulations based on the SD principles. Using general-purpose Web-based software in a SaaS manner, we develop a simplified simulation model capturing the basic supply chain operations.

4. STOCK-AND-FLOW SIMULATION MODEL

Contemporary software solutions that support integrated supply chain operations cover many operations related to the cost, quality, delivery, and flexibility that arise from the very first suppliers to the end consumers. For instance, retailers do not make explicit purchases from distributors anymore; instead, retailers' information systems automatically generate and send purchases, based on the defined minimum levels of products in their internal warehouses, and distributors automatically initiate the transportation of ordered products to retailers, based on their available resources. This is the essence of the proposed supply chain simulation model.

The underlying logic behind the proposed SD simulation model and its boundaries are concisely described with the causal loop diagram, shown in Figure 2.

Causal loop diagrams are a technique to portray the information feedback at work in the observed system. The word 'causal' refers to cause-and-effect relationships, whilst the word 'loop' refers to any closed chain of cause and effect (Ford, 1999, pp. 69–87). Causal loop diagrams are an essential tool used by the SD approach, allowing one to focus on the structure and the dynamic behavior of a given system over time. It portrays the interrelations that exist among different input and output variables, mutually connected by influence arcs that end with arrows (i.e. directed arcs), forming the causal chains and loops. Each arc has two important features: a direction and a sign. The direction of arcs shows the effect of a causal chain, whilst the sign denotes the nature of a change between two variables: when the sign is positive (+), the variables on both sides of the influence arc change in the same direction (e.g. an increase of the value of the variable from which the arc originates implies an increase of the variable to which the arc sinks and vice-versa), otherwise (–) they behave oppositely.

The causal loop diagram depicted in Figure 2 points out the inclusion of three main actors in the SD model, which are a constituent part of any supply chain: the consumers, a retailer, and one of its distributors:

Consumers: the consumer arrival rate (λ), the probability of buying a certain product (π), the mean quantity bought (μ), and the standard deviation of the quantity bought (σ) have all a positive impact on the total quantity bought in a particular retailer's store;

Retailer: the increased quantity bought leads to decreasing the quantity of a product on the retailer's store shelves. After reaching the defined minimum level on store shelves, an internal transfer of a certain quantity of the same product is initiated from the retailer's store warehouse to store shelves. Each internal transfer of products decreases the number of products in the retailer's store warehouse. After reaching the minimum level in the store warehouse, a certain quantity of the product is ordered automatically from one of the retailer's distributors;

Distributor: based on the maximum number of available vehicles, the distributor assigns a certain number of these to transport (a part of) the ordered quantity of the product, based on the vehicles' storage capacity. The more assigned vehicles and/or the larger the vehicles' storage capacity, the more the quantity delivered to a retailer's store warehouse. The increase in the quantity delivered to a retailer's store warehouse imposes an increase in the quantity in the retailer's store warehouse while decreasing the quantity of a product in a distributor's warehouse.

Figure 2 indicates the existence of two balancing loops, which reflect circular causality in the modeled system: the first one encompasses the processes included in the internal transportation of a product from the retailer’s warehouse to the retailer’s store shelves, whilst the second one refers to processes encompassing the transportation of a product from distributor’s warehouse to retailer’s warehouse. In general, a feedback loop exists when information, originating from some action, travels through a system and eventually returns in some form to its point of origin. Feedback is said to be negative (i.e. balancing) when the change fosters other components to respond by counteracting that modification. Feedback is considered positive (i.e. reinforcing) when the original change leads to modifications that reinforce the process. Negative feedback loops are likely to counteract the disturbance and guide the systems back to equilibrium or a steady state. On the other hand, positive feedback loops tend to intensify any disturbance and lead the system away from equilibrium.

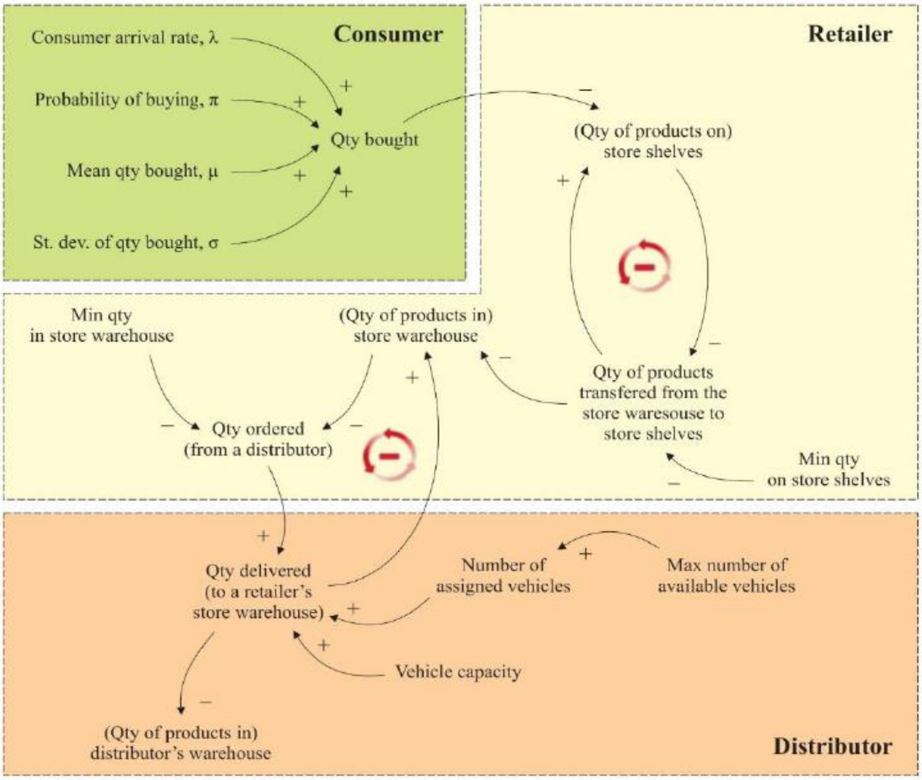

Figure 2. Causal loop diagram depicting the logic and the boundaries of the proposed simulation model

The proposed simulation model (Figure 3) has been completely developed from the causal loop diagram using InsightMaker®, an innovative, Web 2.0-based, multi-user, general-purpose, online modeling and simulation environment, completely implemented in JavaScript, which promotes online sharing and collaborative working in a SaaS manner (Fortmann-Roe, 2014).

In Figure 3, stocks are presented with rectangles, flows with bold directed arrows, and variables with ovals, whilst dotted lines, connecting two primitives, represent links, which transfer information between them.

The specifications of variables, stocks, and flows are given in Table 1, Table 2, and Table 3, respectively.

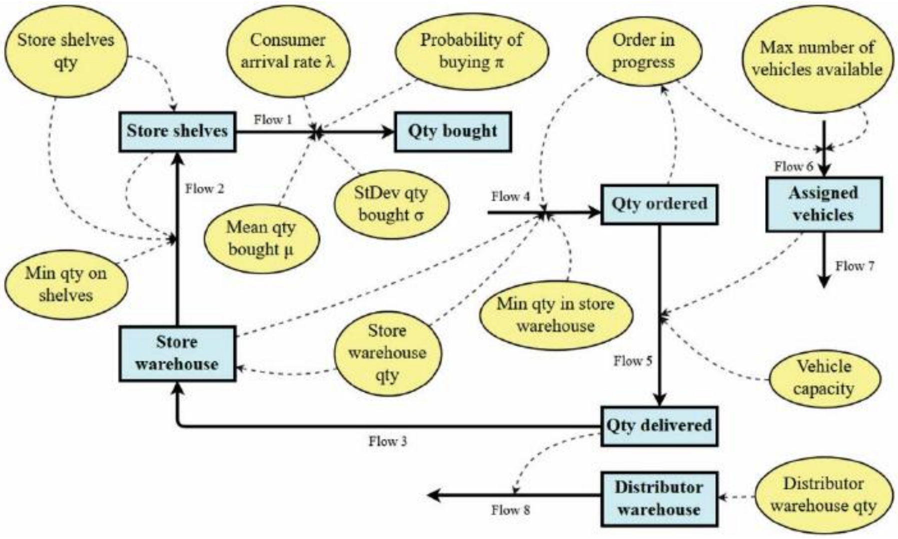

Figure 3. Stock-and-Flow simulation model of basic supply chain operations

Table 1. Specification of variables in the SD model

Object (variable)	Unit	Initial value	Adjustable ?	Min value	Max value	Step
Consumer arrival rate λ	consumers per day	200	Yes	0	1,000	5
Probability of buying π	///	0.05	Yes	0.00	1.00	0.05
Mean qty bought μ	pcs	1	Yes	0	50	1
StDev qty bought σ	pcs	0.75	Yes	0.00	1.00	0.05
Store shelves qty	pcs	50	Yes	0	100	5
Min qty on shelves	pcs	5	Yes	0	25	5
Store warehouse qty	pcs	5,000	Yes	0	10,000	100
Min qty in store warehouse	pcs	500	Yes	0	2,500	100
Order in progress	///	Prog. code	No	///	///	///
Max number of vehicles available	pcs	5	Yes	1	10	1
Vehicle capacity	pcs	25	Yes	10	100	5
Distributor warehouse qty	pcs	500,000	Yes	0	1,000,000	1,000

From Table 1, it is obvious that all variables in the SD model are adjustable, except the variable [Order in progress], which is an internal control variable; it takes its value depending on the output of the following programming code:

If [Qty ordered] > 0 Then 1 Else 0 End If

This variable performs as a semaphore: 0 = there is no ongoing purchase; 1 = a purchase is being serviced.

Table 2. Specification of stocks in the SD model

Object (stock)	Initial value	Meaning
Qty bought	0	Quantity of products being bought from retailer's store shelves by consumers at each time instance
Store shelves	[Store shelves qty]	Total quantity of products on the retailer's store shelves over time
Store warehouse	[Store warehouse qty]	Total quantity of products found in the retailer's warehouse over time
Qty ordered	0	Total quantity of products being ordered by the retailer from the distributor within a single purchase
Qty delivered	0	Quantity of products being delivered at each time instance by the distributor to the retailer within a single purchase
Assigned vehicles	0	Number of distributor's vehicles at each time instance, assigned for transporting the ordered products
Distributor warehouse	[Distributor warehouse qty]	Total quantity of products found in the distributor's warehouse over time

1. SIMULATION RESULTS

Given that the time unit used in simulations is set to 'day', the maximum simulated time length was set up to 1,500 [days]. What follows is a step-by-step verification of the proposed SD model by presenting a series of simulation outputs that portray the dynamics of certain parts of the supply chain over time, thus proving that the modeled system complies with the general idea/specification.

Figure 4 depicts the dynamics within the retailer's store. Due to [Flow 1], which represents the number of products being bought from store shelves daily, there is a continuous decrease of the product's quantity on the shelves from its initial value to the minimum allowed one over time. Once the level of the variable [Store shelves] reaches the value of the variable [Min qty on shelves], an internal flow of products, [Flow 2], activates from the retailer's warehouse to retailer's shelves, filling up instantly the number of products to the value of [Store shelves qty].

Table 3. Specification of flows in the SD model

Object (flow)	Expression
Flow 1	= Round(RandPoisson([Consumer arrival rate λ])*[Probability of buying π] * RandNormal([Mean qty bought μ], [StDev qty bought σ]))

Flow 2	= If [Store shelves]<=[Min qty on shelves] Then
	[Store shelves qty]-[Store shelves]
	Else
	0
	End If

Flow 3	= [Qty delivered]

Flow 4	= If [Order in progress] = 0 Then
	If [Store warehouse] <= [Min qty in store warehouse] Then
	[Store warehouse qty] - [Store warehouse]
	Else
	0
	End If
	End If

Flow 5	= If [Qty ordered] - [Assigned vehicles] * [Vehicle capacity] > 0 Then
	[Assigned vehicles]*[Vehicle capacity]
	Else
	If [Qty ordered] - [Assigned vehicles] * [Vehicle capacity] < 0 Then
	[Qty ordered]
	Else
	0
	End If
	End If

Flow 6	= If [Order in progress] = 1 Then
	Round(Rand(0, 1) * [Max number of vehicles available])
	Else
	0
	End If

Flow 7	= [Assigned vehicles]
Flow 8	= [Qty delivered]

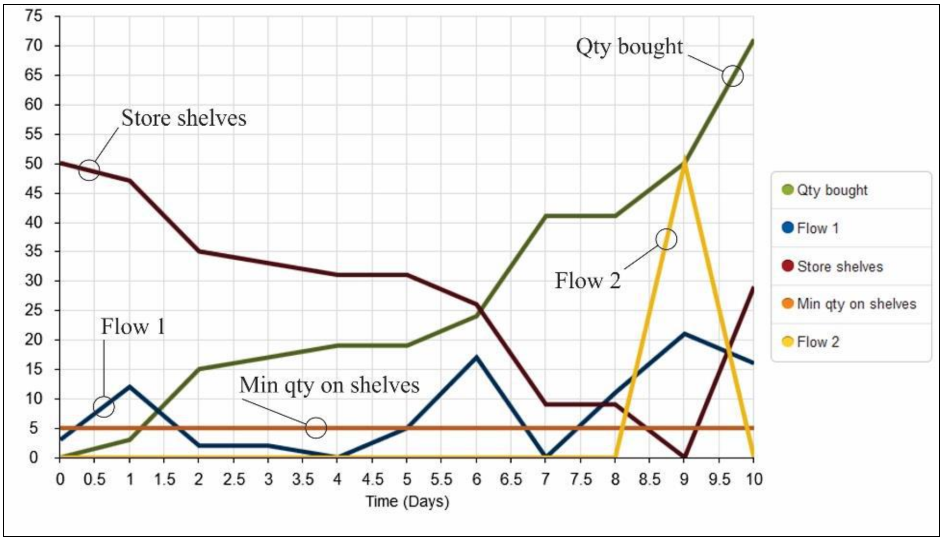

Figure 4.The dynamics with the retailer's store

Consecutive activations of [Flow 2] impose the level of the product in the store warehouse, [Store warehouse], to decrease slowly over time (Figure 5). In Figure 5, the primary axis represents the levels of product quantities in the retailer's store warehouse over time, whilst the secondary axis represents the amounts of the product transferred from the retailer's store warehouse to retailer's store shelves at particular time instances, due to [Flow 2].

Once the current level of the product in the store warehouse, [Store warehouse], reaches the specified minimum, [Min qty in store warehouse], an order is automatically generated and sent to the retailer's distributor, which complements the product's quantity in the store warehouse up to [Store warehouse qty]. This behavior is repeating over time, as long as there are quantities of the product in the distributor's warehouse (Figure 6).

Figure 7 explains the role of the control variable [Order in progress]. It takes a value of 1 at the moment when a purchase to supply additional quantities of the product from the distributor is made by the retailer and takes a value of 0 when the purchased quantities are completely transferred. In the same context, Figure 8 illustrates the role of the control variable regarding the dynamics of assigned vehicles at each time instance, intended to transfer the ordered quantities of the product from the distributor's warehouse to the retailer's store.

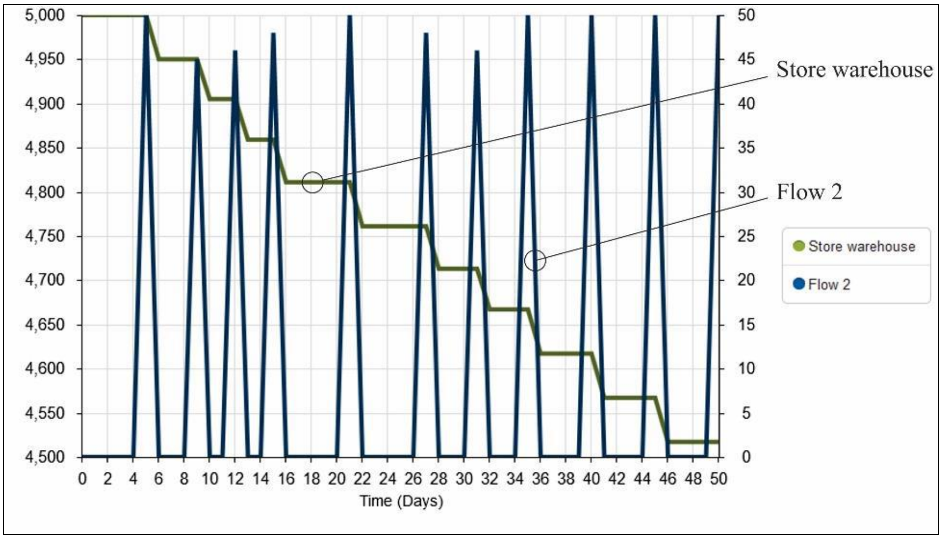

Figure 5. Decrease in product quantities in the retailer's warehouse as a result of many consecutive transfers of products to the retailer's store shelves

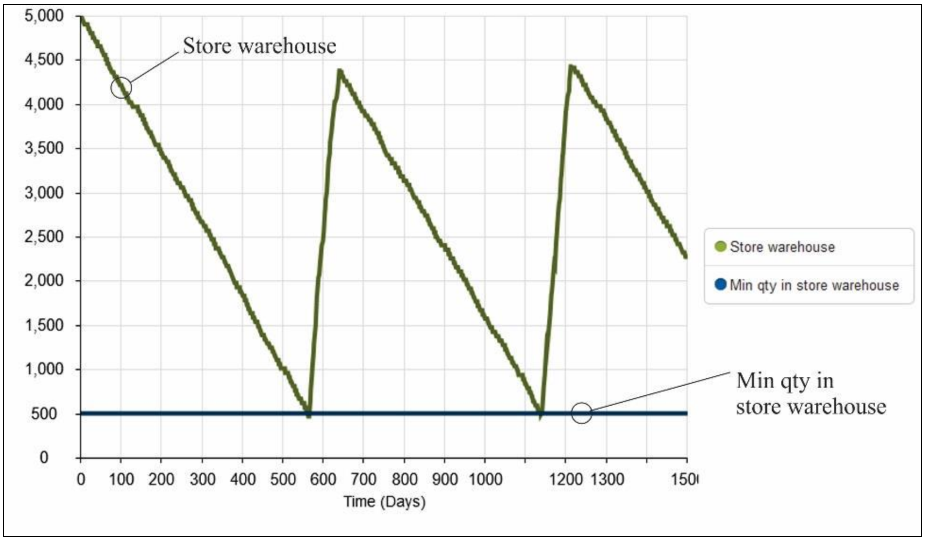

Figure 6. Cyclic complementing product quantities in the retailer's store warehouse over time, as a result of reaching the specified minimum

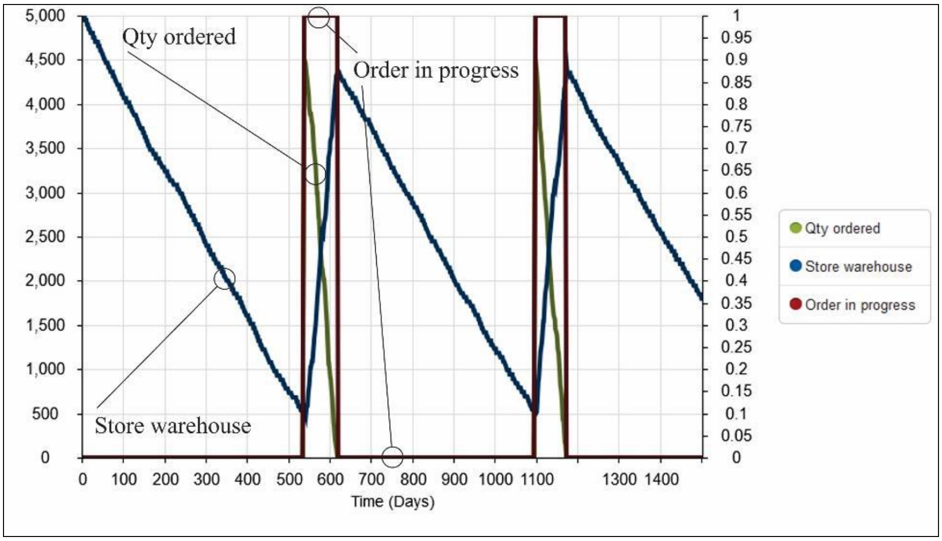

Figure 7. Illustration of the variable [Order in progress] vis-à-vis the timing of placing and fulfilling purchases

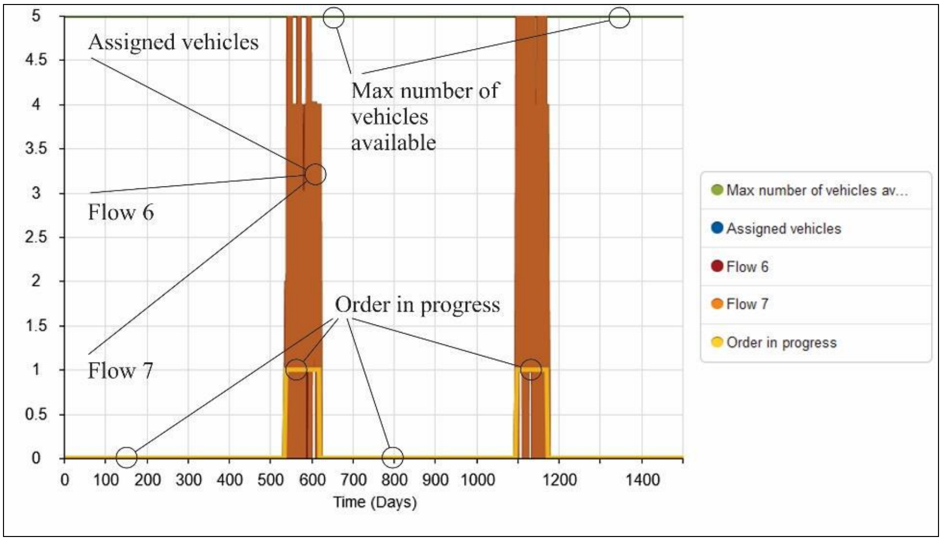

Figure 8. Illustration of the variable [Order in progress] vis-à-vis the number of assigned vehicles

Finally, Figure 9 shows the decrease of product quantities in the distributor's warehouse over time (primary axis), as a result of [Flow 8], representing the transfer of purchased quantities to the retailer's store warehouse at particular time instances (secondary axis).

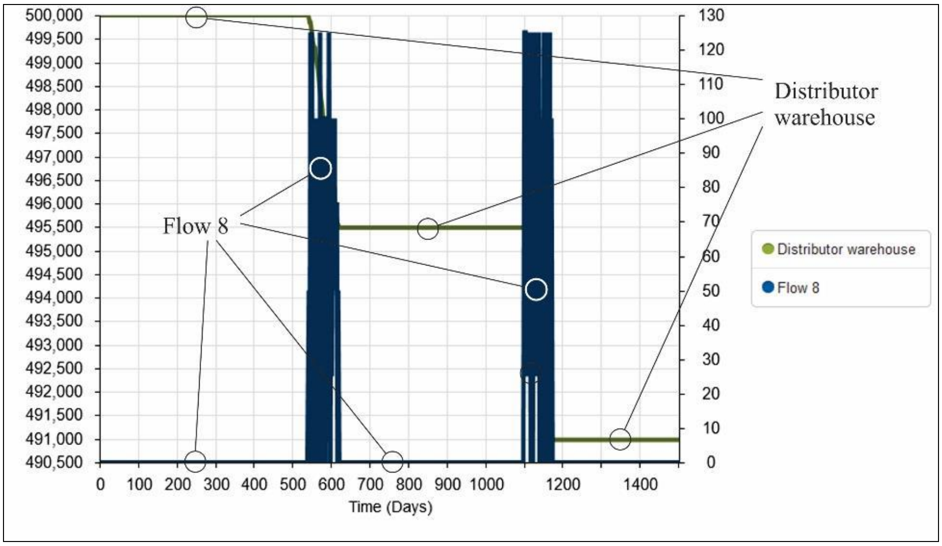

Figure 9. Decrease of product quantities in the distributor's warehouse [Distributor warehouse] over time, as a result of [Flow 8]

2. CONCLUSION

Simulation enables the design of a supply chain and evaluation of SCM before the implementation of the real system, which allows one to perform 'what-if' analyses leading to 'the best' (i.e. the optimal) decision/solution. As such, simulation of supply chains can be used to support supply chain design decisions or evaluation of supply chain policies.

The power of simulation as a methodology for analysis shows up whenever the observed supply chain is complex, dynamic, and has transient (i.e. time-dependent) performance problems. In general, simulating a supply chain can be extremely complex, because the underlying model must capture well many crucial business processes, including the basic material requirements planning (MRP) process, planning, and scheduling, capital acquisition, labor policies, allocation of constrained resources, etc. However, if a supply chain is modeled correctly, a supply chain simulation can show ways to increase revenues, profitability, and service levels to the customer. This can translate into large financial advantages for the company.

The proposed generic SD model allows making thorough insights into the dynamics of the modeled supply chain. Since it captures solely the basic operations among the last three actors in a supply chain (i.e. 'the last mile'), it has many limitations, including the following ones: (a) The supply chain refers to a single product, a single retailer store, and a single distributor; (b) The distributor uses vehicles all having the same storage capacity; (c) In order to restrict the model to only three actors (i.e. consumers, retailer, and distributor), the distributor warehouse capacity is theoretically infinite (i.e. sufficiently large in practice). Contrary to verification, which was carried out as an internal process, validation of the modeled system, which is the process of assuring that it meets the needs of a customer and other identified stakeholders (i.e. its end users), was not possible to be carried out at this point, since the proposed simulation model is generic and in an early stage of development. Yet, the model is quite flexible in two ways: (a) the 11 adjustable parameters offer a plethora of possibilities to run various 'what-if' analyses and test various simulation scenarios; (b) the SD model can be easily upgraded by including additional variables to assess various categories of interest, like costs related to human resources, transportation, storage of products, etc.

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