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Modeling Supply Chain Disruptions During a Pandemic: A System Dynamics Approach

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Abstract: The COVID-19 Pandemic of 2020 uniquely impacted the janitorial supply industry with shocks in both demand and supply. Some products experienced massive increases in demand leading to shortages, while the closing of public spaces caused a decrease in demand of other products. The industry experienced delays in shipping and production because of factory closings. Changing public policies for hygiene standards in public buildings, schools, and government buildings has led to a sustained increase in demand for certain products. The janitorial supply chain is a dynamic system that continues to experience change as the pandemic and the public response to it evolves. This research uses a System Dynamics approach to model a small janitorial supply business' inventory both before and during the pandemic using Vensim. The model focuses on the main categories of products the business sells (Paper Products, Chemicals, Aerosols, and Garbage Bags) and how their respective flows of supply and demand are affected. The business purchases some products directly from manufacturers and others from larger distributors. It sells primarily to the following categories of customers: government contracts, factories, businesses, and individual walk-in sales. Ultimately, this model explores practical policies the store could implement to make them more resilient to the extreme levels of uncertain supply and demand caused by the pandemic. Implementing inventory minimums for sales and safety stocks for orders improved the number of sales and increased revenue for the business during pandemic simulations. Safety stocks and inventory minimums prove to be useful policies for small businesses to consider to become more resilient and survivable to a pandemic.

Keywords: System Dynamics, Supply Chain, Pandemic, Janitorial Supplies, Inventory Management

1. Introduction

The COVID-19 Pandemic that began in 2020 has uniquely impacted the janitorial supply industry. During 2020, janitorial supply experienced shifts in both the population of customers and the demand associated with specific products. When the pandemic first spiked in early 2020, many schools and non-essential businesses closed, shifting the demand for cleaning supplies from commercial to the home (Kaplan 2020). This led to a large shortage in supply and suppliers had to increase production to catch up. The boom in janitorial supply demand led to companies such as Clorox reaching record high stocks, individual households stockpiling cleaning supplies and personal hygiene goods, and prices on some products marked up as much as 2,000% (GEP 2016). As the pandemic advanced, previously closed businesses, factories, government buildings, and schools began to reopen, but with heightened cleaning procedures and requirements (Kaplan 2020). New policies for cleanliness and sanitation standards also created a greater need for cleaning supplies. This research analyzed a single janitorial supply distributor in Kentucky as a case study of the pandemic's impact on a unique industry. The main goal of this research was to explore practical policies that a small business could implement to become more resilient to a future pandemics or events that cause extreme uncertainty in supply and demand. This paper follows the System Dynamic Modeling Process to develop a simulation model of inventory flowing through the janitorial supply store both before and during the pandemic. Vensim was the modeling software used to create this model.

2. Stakeholder Background

A small, family-owned janitorial supply retailer and wholesaler in southern Kentucky named Southside Supply was the case study for this research. Detailed information about the company was gathered from personal interviews with the owner, general manager, and warehouse manager. The firm offers wholesale prices for products bought in bulk, cleaning services, and free delivery to customers within the surrounding counties. Additionally, Southside staff offers construction site clean-up and daily cleaning crews for nearby factories and businesses. The store is open to the public, but most customers fall into one of the following four categories: government contract or public buildings, factories, businesses, and walk-ins. Southside sells a wide range of products, including medical and food service supplies, but most product sales fall into the following four categories: paper products, chemical products, aerosol products, and garbage bags (Owner, personal communication, January 6, 2021).

Southside orders some products directly from the manufacturer and others from larger distributors depending on whether they can meet the required purchase minimum. They sell enough chemicals, aerosols, and garbage bags on a regular basis to order directly from the manufacturer. By ordering directly from the manufacturer, Southside can use a unique branding label on products and get them at the lowest price. However, Southside does not sell enough paper products (toilet paper, paper towels, etc.) or have ample storage space to justify buying directly from manufacturer. Instead, Southside orders paper products from a larger distributor that allows purchasing in smaller quantities. The nearest paper distributor has three warehouse locations, two in Nashville and one in Indianapolis. All locations are within a day's drive by truck (Warehouse Manager, personal communication, January 2,2021).

During the summer of 2020, Southside reportedly experienced the effects of the pandemic as products from both the distributor and manufacturers were delayed or unavailable at times. Delays likely sourced from a higher level than transportation because the business owner reported very few missed deliveries. Trucks would arrive on time each week but rarely with a complete order. Additionally, Southside experienced different shifts in demand for each product category and each customer group. Walk-in demand increased for some products that became scarce at other large retailers while government and small business demand decreased as businesses closed. Shifts in demand and product availability are just two factors in a very complex and dynamic system created by the pandemic. The client needs practical policies that can be implemented at their level to become more resilient and survive the pandemic.

3. Methodology

The System Dynamics Modeling Process (SDMP) is a methodology for modeling complex, dynamic systems to predict system behavior over a given time horizon (Sterman, 2000). The SDMP was selected as the methodology for this research because of the dynamic nature of janitorial supply during the pandemic. The entire modeling process is iterative meaning that the results of one part can lead to insights in another. The whole process is connected and does not necessarily occur in a linear fashion. The first step is Problem Articulation, where a basic understanding of the problem and system occurs. The system boundary is identified by clarifying the scope, key variables, and time horizon. This step also includes the formulation of a Dynamic Hypothesis. This is an initial hypothesis of the dynamics of the endogenous system behavior (Sterman, 2000). The next step is to begin formulating the model. This starts with the creation of a causal loop diagram and then transitions into the development of a stock and flow diagram. After developing a functioning model, the next step is to test the model's legitimacy to ensure it effectively captures the system and problem at hand. This involves testing extreme conditions, sensitivity analysis, and dimensional consistency. Finally, the last step is to design, implement, and evaluate a system policy to address the problem. Different policies are simulated, and the subsequent system behaviors compared. Ultimately, a policy change will be recommended to the stakeholder.

3.1 Problem Articulation

To understand the problem, Southside Supply's inventory system was simplified to show how inventory flows through the store. Products inflow directly from manufacturers and from larger distributors. Products outflow to the four main customer types. The system diagram in Figure 1 depicts the structure of inventory flow. The system diagram was created based on information gathered during interviews with the business owner. The main problem expressed by the stakeholder was that uncertainty in supply and demand caused by the pandemic led to selling out of products quickly without the ability to restock. The initial increase in sales was profitable, but unsustainable when the next opportunity to restock was uncertain (Owner, personal communication, January 2,2021).

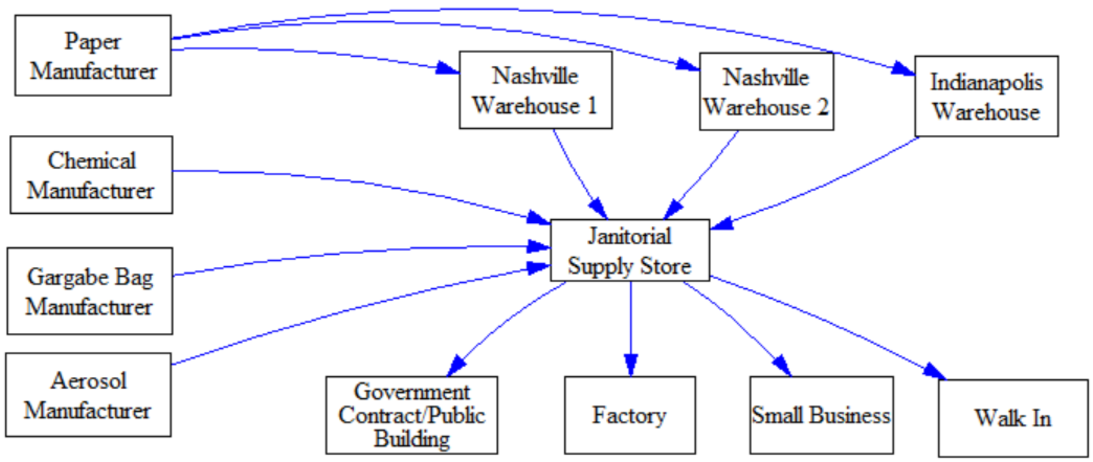

Figure 1. System Diagram for Southside Supply

3.2 System Boundary

The scope of this model was narrowed by defining the system boundary for Southside's inventory in terms of endogenous, exogenous, and excluded variables. Endogenous variables are internal to the system being modeled while exogenous variables are inherently external (Sterman, 2000). Exogenous variables influence the behavior of endogenous variables which, in turn, influences the behavior of the system. Endogenous variables are stocks and flows internal to the system and directly influence the inventory management of each product. These variables include the inventory, demand, availability, and shipping of each product. The impact of the pandemic and demand of each customer type are accounted for as exogenous variables. Explicitly stating excluded variables clarifies what the model will not address. This model does not include other janitorial supplies or services, medical supplies, equipment sales, installation and services, and competition within the market. Additionally, the model and policies discussed later in this research focus only on what the individual firm can control to provide a useful recommendation. The scope does not include anything in the overall janitorial supply chain system before the products arrive at Southside. Defining and narrowing the scope reduces complexity and focuses the analysis of the system.

3.3 Key Variables

Before constructing the model, key variables necessary to capture all aspects of the problem were identified and assigned a unit. The unit of time in this model is "Week", and the key variables include both stocks and flows. All stocks have the unit "Cases" while flows have the unit "Cases/Week". For each product type, the model includes the variables of Store Inventory, Expected Sales, and Desired Inventory, all with the unit "Cases". Finally, demand of each customer type is captured by a fractional multiplier of the expected sales variable of each product. The demand fractions are dimensionless as they solely represent a customer type's contribution to the total demand. Table 1 lists the key variables later included in the model.

Table 1. Key Variables for the Janitorial Supply Store System

Variable	**Units**	**Variable**	**Units**
Product Inventory	Cases	Products Sold	Cases
Order Rates	Cases/Week	Desired Inventory	Cases
Shipping Time	Weeks	Inventory Gap	Cases
Demand Fractions	Dimensionless	Inventory Policy (Minimum Percentages)	Dimensionless
Sales Rates	Cases/Week	Product Price	Dollars/Case
Expected Sales	Cases	Product Revenue	Dollars

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3.4 Time Horizon

The time horizon for this project is one year (52 weeks). One year effectively captures normal system behavior and the system's response to the pandemic. 'Weeks" is the unit of time in the model because it allows for the analysis of rapidly changing system behavior. Southside delivers products and makes orders weekly, so it aligns well with the system under study.

3.5 Dynamic Hypothesis

An increase in demand for a particular product without the ability to simultaneously increase supply will inevitably lead to the inventory becoming out of stock. Imposing a policy of required inventory minimums along with incorporating safety stocks in product ordering will delay the effects of the pandemic and allow the business to sustain a more normal operation for longer (S. Herbert, personal communication, October 2020). The inventory minimums limit sales of a product when its inventory approaches a lower threshold. Ideally, the policy will find the balance between holding the right amount of stock to survive to the next time period while also selling enough in the present to remain profitable. The concept of a safety stock creates a buffer in inventory to account for unexpected demand. More product is ordered than forecasted to sell in that time period. A commonly used method of calculating safety stocks is to multiply the average demand per day by a safety time margin that accounts for the time required to fully restock inventory (Jonsson, 2019). This portion of the policy also has a tradeoff between increasing upfront cost to order more product and the opportunity for more profit if an unexpected spike in demand occurs.

4. Model Formulation

4.1 Causal Loop Diagram

Figure 2 is a Causal Loop Diagram (CLD) that visually depicts the system with information gathered from stakeholder interviews. This diagram shows relationships and influence within the system depicted by causal links (arrows) (Sterman, 2000). The causal links represent the feedback structure within the system by assigning a polarity, positive or negative, to the relationship. Figure 2 clearly has the janitorial supply store as the center of all influence in the system with the supply aspects represented on the left and demand on the right. Starting on the outside, the pandemic's effects on the system by directly influencing customer demand and production. The direct impact of the pandemic is categorized as first-order effects. Working toward the center of the CLD, the second-order effects of the pandemic influence system behavior through delays in production, delays in shipping, business closures, and other social impacts (Del Rio-Chanona, 2020). Ultimately, the pandemic impacts the feedback structure that propagates through the system. The dynamics of this system are analyzed further in later phases of modeling.

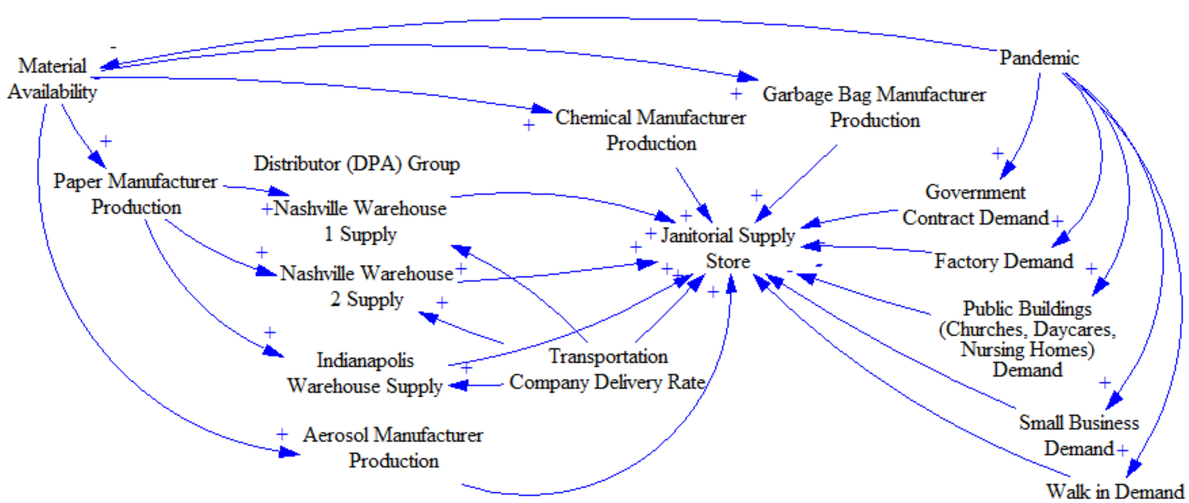

Figure 2. Causal Loop Diagram for the Janitorial Supply Store System

4.2 Stock and Flow Diagram

Figure 3 is the resulting stock and flow diagram (SFD) created from the CLD in Figure 2. The SFD shown is a portion of the model representing only one product type, but this basic structure repeats for each product. All initial values of for the variables in the model were gathered from stakeholder interviews and are displayed in Table 2. Ultimately, the SFD depicts the flow of inventory through the store. The inventory gap variable and manufacturer delivery time determine the order rate of each product. The store has a desired inventory value for each product which, when compared to the actual inventory, creates the inventory gap variable. The sales rate of each product is a function of expected sales, delivery time, and an inventory minimum. Each main customer type has a fractional impact on the expected sales. The SFD is the foundation of the model and simulates the store under normal operating conditions. The final portion of the SFD shown on the far right of Figure 3 was developed to eventually assess the economic benefit of future policy implementation. The average price used in the simulation was taken from a wholesale janitorial supply catalog and does not represent real financial data from the stakeholder (Bauman Paper Company).

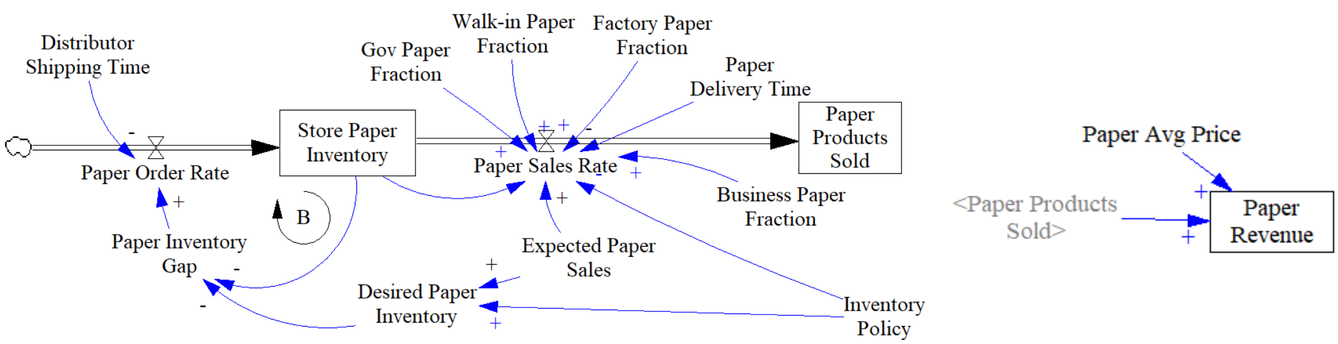

Figure 3. Stock and Flow Diagram for the Paper Inventory of Southside Supply

In order to capture effects of the pandemic, the fractional expected sales of each customer were increased by values expressed by the stakeholder (Table 2). For example, under normal conditions walk-ins accounts for 5% of paper sales, and during the pandemic, walk-in's paper product demand increased to 20%. This technique was applied to each customer type demand fraction for each product. Additionally, to model potential policies of inventory minimums, the sales rate of each product contains a conditional function based on the proposed inventory minimum. If inventory of a product drops below a specified minimum value, the sales rate becomes zero. In other words, sale of a product halts until the minimum inventory amount is exceeded again.

Table 2. Demand Fractions of Each Customer During Normal Operation and the Pandemic

Demand Fractions (Normal/Pandemic)								
	Paper		Garbage Bag		Chemical		Aerosol	
Walk-In	0.05	0.2	0.05	0.05	0.15	0.25	0.2	0.3
Factory	0.2	0.2	0.25	0.25	0.3	0.35	0.15	0.5
Government	0.4	0.3	0.35	0.35	0.4	0.5	0.35	0.55
Business	0.35	0.3	0.35	0.35	0.15	0.25	0.3	0.25

The SFD accounts for availability of products through the distributor or manufacturer shipping time and Southside's delivery time. During normal operation, Southside receives weekly shipments from their suppliers and make weekly deliveries to their customers. The warehouse manager stated that the trucks still arrived on time but did not always have the full order during the pandemic. He estimated that it took approximately a month to get shipments of products previously ordered (Warehouse Manager, personal communication, January 2,2021). During simulations of the pandemic, the shipping time parameters were increased to four weeks instead of one week to account for this estimation and variability in product availability.

5. Model Testing and Analysis

5.1 Model Testing

Model testing occurred throughout the development of the model since the SDMP is an iterative process. The mapping of the system diagram, CLD, and SFD confirmed boundary adequacy, the first model testing technique. Secondly, the stakeholder verified the structure of the model through interviews and presentation of sample iterations. The third technique used for model testing was dimensional consistency which ensures there are no errors in the functions and units are used correctly. Finally, the model was simulated under extreme conditions to test if it responds appropriately and follows a logical behavior. The extreme conditions tested were the parameters of normal operation and during the pandemic. The model held up under those conditions meaning it can now effectively test for policies with parameters in between the normal operation and pandemic extreme conditions.

5.2 Model Simulation and Policy Implementation

The SFD in Figure 3 was simulated under the normal operating conditions and the pandemic conditions as outlined in Table 2. Additionally, three policies were tested under the pandemic conditions to explore which would be more beneficial for the stakeholder to implement. Policy 1 implemented a 20% inventory minimum and ordered 20% safety stock. Policy 2 and 3 follow the same pattern and increase the values to 30% and 40%, respectively. The simulation iterates for 52 weeks; however, Figure 4 presents output data from the simulation from a 12-week time period to better observe system behavior. The same pattern of behavior repeats over the time horizon. Additionally, this section focuses on outputs of only one product type for simplicity. The other products experience similar behavior only with differing model parameters (Table 2). During normal operation, inventory oscillates suggesting a limit cycle behavior (Sterman, 2000). The oscillations are stable and expected each cycle as customers buy the product and inventory decreases. The products are ordered again causing the stock to rise. This same oscillatory behavior is also seen in the sales rate. The sales rate behavior for normal conditions was not included in the right graph of Figure 4 to allow for better understanding of the policy implementation. However, it is simply the inverse of the inventory behavior. When sales peak, inventory drops and vice versa. The system behavior during the pandemic followed as expected. Inventory decreased as sales increased, and it took nearly nine weeks for inventory to return to acceptable levels just to plummet again.

The policies tested for safety stocks and inventory minimums appear to be successful solely from an inventory perspective. The economic benefit will be explored next in Figure 4. Implementing an inventory minimum and ordering surplus stock allows the inventory to rebuild to acceptable levels quicker and the store to resume sales sooner. Policy 3 completes two full restock and resale cycles during the 12-week period where Policy 1 only completes one cycle. Increasing the inventory minimums suggests that the system will approach more normal behavior. Shipping delays will not allow the system to completely achieve normal behavior, but the policies implemented do achieve healthier inventory cycles.

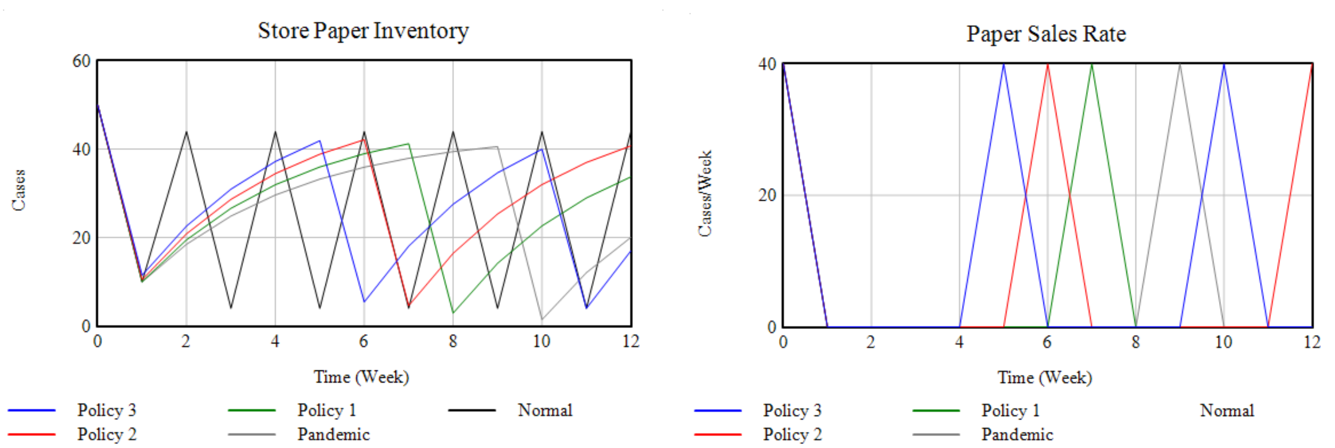

Figure 4. Paper Product Inventory (Left) and Sales Rate Under Different Policy Conditions (Right)

Figure 4 suggested that the implementation of a proposed policy would be beneficial for the stakeholder. Figure 5 supports those same findings with the economic benefits of each policy. Normal operation follows a nearly linear relationship for products sold. The pandemic caused steep increases of products sold when products are available and then no flow of products at all until a restock occurred. Each policy applied follows a similar, but improved, behavior as that of the pandemic. Shipping delays still cause a period of no sales, but the increase in inventory minimums does suggest a higher total of products sold each year. Holding stock of a product does not inherently seem intuitive because of the opportunity to sell it now and make a profit. However, the discipline to temporarily implement a minimum stock and safety stock policy could make the store more resilient and more likely to survive. The tested policies increased sales from the baseline pandemic simulation which subsequently increased revenue for the year. They did not perform nearly as well as normal operation, but it is still an improvement from having no policy during the pandemic. The results are promising because inventory minimum polices are practical for small businesses to implement (Chopra, 2004).

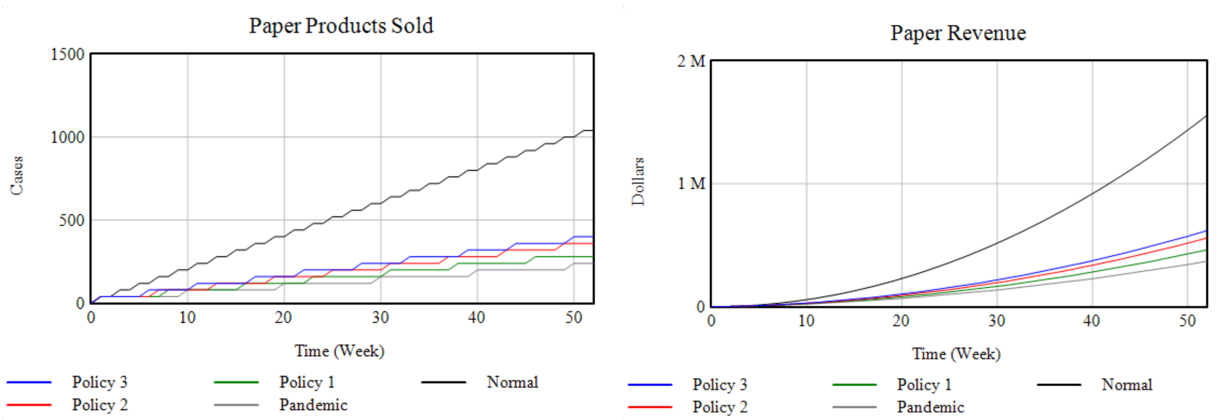

Figure 5. Cumulative Paper Products Sold (Left) and Revenue for a Year Cycle (Right)

6. Conclusion

Modeling a janitorial supply store during a pandemic has shown that temporary, drastic shifts in demand and delays in shipping can have a large impact on the capability to manage and maintain inventory. The SDMP was used to model a small janitorial supply company as a case study for inventory management during times of uncertainty in supply and demand. The policies explored in this research suggest that requiring an inventory minimum before selling and increasing orders to have a safety stock could allow a retailer to be more resilient or survivable to a pandemic. “Firms mitigate uncertainty in demand and supply by carrying safety stock, planning for excess capacity and diversifying supply sources” (Jonsson, 2019). This research explored the impacts of ordering safety stock, or excess product, and found it to be a useful technique. The model results suggest that the higher the inventory minimum is, the more products the firm will sell during a year in a pandemic. However, this is likely not the case in practice. The model has limitations and does not account for every aspect of the highly complex system. The stakeholder should take these findings into consideration when developing a policy and find a practical balance of holding product to survive to the next cycle and selling enough now to pay employees and other fixed expenses. Implementing a safety stock policy would inevitably increase the upfront cost of acquiring supply, but it would also allow the firm to have a buffer of excess supply in the event of increased demand.

6.1 Recommendation for Future Work

A potential policy to explore would be the diversification of manufacturer or distributor sources. This would decrease the reliance upon a single manufacturer and could help maintain a steady supply (HBR IdeaCast, 2020). A second policy to investigate would be altering the delivery time from the janitorial supply store to the customer. Delaying orders or delivering fewer times a month may have a similar effect as the inventory minimums. It could slow the negative impacts of the pandemic on inventory.

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