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SYSTEM DYNAMICS SIMULATION OF EXTERNAL SUPPLY CHAIN DISRUPTIONS ON A SIMPLIFIED SEMICONDUCTOR SUPPLY CHAIN

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ABSTRACT

Due to the vitality of semiconductor products for other industries, the production of semiconductors and impact of external disruptions on the semiconductor supply chain should be well understood. As semiconductor manufacturing is accompanied with intrinsic long manufacturing cycle times ranging from 50 to 100 days where operations run 24/7, 365 days per year, correct understanding of potential disturbances should be considered. Examples of these disturbances include pandemics, extreme weather events, geopolitical tensions and war. These hazards pose various risks for supply chains, for example, the bullwhip and ripple effect. To simulate the result of such risks, a simplified system dynamics model of a typical semiconductor manufacturing supply chain was constructed using the Anylogic Software. The model serves as a what-if scenario foundation to evaluate certain external circumstances dependent on current global situations to enhance supply chain resilience.

1 INTRODUCTION

Due to the complexity of the semiconductor supply chain, which is explained mainly by its global dispersion of the various manufacturing steps, long cycle times and capital-intensive manufacturing equipment, external disruptions that occur in one node may potentially impact the performance of the entire supply chain. Supply chain disruptions can be in the form of a man made or natural hazards. Some examples are geopolitical tensions, pandemics and extreme weather events that occur unexpectedly. Unforeseeable events can lead to inaccurate amplification of impacts known as the ripple effect and some of these consequences can be, among others, inaccurate demand, inventory fluctuation, and increased supply risk (Dolgui and Ivanov 2018).

In addition to the convoluted supply chain structure, semiconductors must always be up to date and pursue advances in technological innovation while maintaining low cost. Moore's law explains that technology's speed and capacity double every two years, increasing the number of transistors a microchip contains (Moore 1965).

To gain a better understanding of how the events influence the supply chain, four risk categories were identified based on the nature of the event and then modeled using system dynamics (SD) to capture capacity, workforce, transport and customer order fluctuations' influence on the stock levels as well as the stock monetary value. Maintaining and enhancing supply chain resilience is an essential concept to be able to reduce adverse effects from hazard events on the firm.

System dynamics allows for high levels of abstraction and complexity which was the focus of this study. Using the production model introduced in the book "Business Dynamics, Systems Thinking and Modeling for a Complex World" (Sterman 2000), four SD models were constructed and strung together to create a simplified supply chain of an inhouse semiconductor manufacturing supply chain. The supply chain consists of Frontend Manufacturing (FE), Diebank, Backend Manufacturing for Available to Promise (ATP) generation and, finally, the usage of ATP in the Distribution Center.

This paper is organized as follows: Section 2 presents the background followed by the description of the methodology in Section 3. The results of the simulation model are discussed in Section 4. Finally, the paper ends with concluding remarks and managerial insights in Section 5.

2 BACKGROUND

2.1 Supply Chain Disruption

As previously explained, the structure of semiconductor supply chains has a high degree of global complexity. Various global entities increase vulnerability to external disruptions, which are defined as "an interruption in the flow of process that involves any of the entities associated with the production, sales, and distribution of specific goods or services" (SafetyCulture 2023). Supply chain disruptions can be in many different forms and can be categorized in the following different sorts: disasters, delays, systems, intellectual property, forecast, procurement, customer quantity, inventory and capacity. The disruptions have varying frequencies and severity dependent on their nature. In addition, a disruption can be local or global, so as local disruptions only occur in one area along the node whereas global events impact different nodes at the same time (Katsaliaki et al. 2021). Examples of recent disruptions that have majorly impacted the interconnections of supply chain are: the COVID-19 pandemic and how it induced a 200-billion-dollar loss in the automotive sector in 2021 due to a semiconductor shortage; heightened trade tensions between The United States of America (USA) and China; the 2011 earthquake and tsunami in Japan; the 2021 blizzard in Austin, TX and the Russian invasion of the Ukraine. When disruptive events, either man made or natural, occur, supply chains can be susceptible to detrimental loss across their entire scope. The amplification of the disruptive event past its origin of impact is known as the ripple effect. The ripple effect is a phenomenon that is provoked by a disruption that occurs at one node in the supply network and its impacts transcend downward to following nodes. The impacts that are dispatched across the entire supply network often lead to negative business effects such as revenue loss, delivery delays, market share loss and reputation loss (Dolgui et al. 2021). The propagation of the ripple effect from its original disruption location generally gains strength as it proliferates throughout the supply chain. The ripple effect is caused by exceptional disruption risks rather than by recurrent operational risks as it is the case for the bullwhip effect (Ivanov and Dolgui 2014). The impact of the ripple effect highlights vulnerabilities within the supply network and pinpoint growth areas for resilience measures within the system. Due to the complexity of modern supply chains, with many global locations, the ripple effect arising from disruptions has an increased plausibility (Llaguno et al. 2022). The ripple effect, also known as the domino effect, is derived from external supply network disruptions, for example natural disasters, local conflicts, terrorist attacks or economic downturns (Wieteska 2018). To mitigate the adverse effects of the ripple effect on supply networks, companies can focus on increasing their resiliency of the supply chain. Recognition of company vulnerability to disruptive events or risk can guide resiliency measures.

The existence of a geographically diverse supply chain as well as intra-network dependencies poses risk to the company of operation via exposure to many uncertainties spread across all entities. These risks, also known as supply network disruptions, are not a rarity. Instead, disruptive events that change supply and demand structures are common to supply chains in all industries. However, in the past four years supply chains within every industry have had heightened and exacerbated instabilities in supply networks and consequent business operations restrictions due to the before mentioned events, such as the Ukraine invasion and extreme demand fluctuations in response to the pandemic. In order to remain competitive, businesses should enable supply chain resiliency, a concept explored in the following subsection, within their supply networks to better counteract disruptive events.

2.2 Supply Chain Resilience

Supply chain resiliency, further referred to as “SC resilience”, is a well-established concept that has been heavily studied within the past years, especially due to the increased frequency in large disruptive events, also known as “black swan events” such as COVID-19. However, there are slight deviations between the definitions presented in the various studies.

SC resilience has been defined as “The ability of a system to return to its original state, within an acceptable period of time, after being disturbed”, which is more oriented to the system’s response, whereas another study explains SC resilience as “The ability to proactively plan and design the supply chain network for anticipating unexpected disruptive (negative events), respond adaptively to disruptions while maintaining control over structure and function and transcending to a post robust state of operations, if possible a more favorable one than that prior to the event, thus gaining a competitive advantage”, a definition that, on the other hand, also includes proactive measures (Tukamuhabwa et al. 2015; Ribeiro 2019). More specifically, Tukamuhabwa et al. (2015) defines supply chain resilience as the ability to withstand and recover from disruptions quickly at a minimal cost. A majority of the research regarding supply chain resilience refers to it as the ability to bounce back or return to the pre-disruption equilibrium state (Tukamuhabwa et al. 2015).

Alternatively, Wieland and Durach (2021) argue that SC resilience should also include the social-ecological concept of resilience to its definition, which is built upon the theory of an organism’s ability to persist and adapt through disruption. The social-ecological definition of resilience stems from the field of ecology and places more emphasis on adaptability to a disruption, with a better outcome than prior to the disruptive state. This concept highlights how disruptions are opportunities to improve the systems’ response and coping ability with a heightened state of operation rather than just bouncing back to the pre-disruption state with the same vulnerability. Therefore, Wieland and Durach (2021) include the social ecology principle to the definition of supply chain resilience describing it as “the capacity of a supply chain to persist, adapt, or transform in the face of change”. Similarly, in the study “Supply chain resilience: definition, review and theoretical foundations for further study”, the authors also integrate this concept and define supply chain resilience as “the adaptive capability of a supply chain to prepare for and/ or respond to disruptions, to make a timely and cost-effective recovery, and therefore progress to a post-disruption state of operations” (Tukamuhabwa et al. 2015).

Resilience according to the field of ecology is comprised of potential and connectedness of the system under study. Potential can be explained as the capacity in which a system can change dependent on the resources it consists of. Connectedness describes how flexible or rigid a system is. The more flexible it is, the higher resiliency it has. If a system’s characteristic allows for higher adaptability in response to a disruption then it is well connected and has higher resiliency (Wieland and Durach 2021).

The condition of a supply network can be simply described in four steps: readiness, response, recovery and growth. The social-ecological definition also states that a system that regularly undergoes disruption and is able to adapt will have better long-term benefits than a system who does not face disruption. Disruptive events allow for reorganization and therefore act upon weaknesses that enabled the impact of the disruption upon the system in a way that, if a similar disruption were to occur again, the system should be able to deal with the consequences with smaller magnitude impacts, as it has already adapted (Tukamuhabwa 2015). The time in which a system or a supply network can respond is another crucial element to supply chain resilience and related to systems adaptability. The quicker the adaptation, the more resilient the supply network is.

Spieske and Birkel (2021) extend the definition of supply chain resilience to also include the network’s ability to withstand, adapt, and recover from disruptions in order to meet customer demand and retain performance. Resilient supply chains and networks have competence to mitigate, adapt, or endure disruption shocks. Mitigation can be achieved by the absorptive capacity, where the system can uptake the impact and alleviate the adverse effects. Examples of this include: multiple sourcing, supplier segregation and adequate inventory levels. On the other hand, adaptation comes into play when the system cannot dissipate the impact but needs to change some of its internal characteristics. This can be in the form of back-up suppliers, rerouting flexibility, manufacturing flexibility or increased communication throughout the network. If supply chains can neither mitigate nor adapt to disruptions, they must recover from them. Finally, recovery explains the final capacity of restoration and its best example is any rehabilitation of the supply chain network, such as facility, manpower, or technological rebuilding (Spieske and Birkel 2021).

In addition to capabilities, there are key characteristics that make up supply chain resilience. These include: visibility, velocity, agility, collaboration, resilient culture, and supply chain re-engineering, which consists of sourcing, design and understanding. Visibility, velocity and agility refer to the ability of the system to react to a disruption in a timely manner. Collaboration and resilient culture are determined by the motivation of management and other cooperating partners to engage in resilient practices. Supply chain re-engineering is concerned with how the supply chain adaptation measures can respond and refers to the design of the adapted network structure (Spieske and Birkel 2021).

In summary, supply chain resilience, also referred to as “supply network resilience”, refers to the ability of a supply chain or network to respond to a disruptive event in an effective time, as well as to implement action plans into place in anticipation of another disturbance. For the purpose of the following simulation constructed focused on resilience, the definition of supply chain resilience is as follows:

Supply chain resilience is the ability of a network or a system to adapt in an efficient manner to reoccurring disruptions to enable an improved state of operation compared to its pre-disruption state. In addition, a resilient supply chain anticipates future disturbances and proactively implements measures to reduce the adverse effects on the network. Lastly, a resilient supply network focuses on adaptability as well as agility, collaboration, active management, and alternative lines of defense.

2.3 System Dynamics Simulation

Simulation is one of the most applicable methods for modelling and studying complex systems such as complex manufacturing supply chains. System Dynamics (SD) simulation in particular has been widely employed to analyze multi-echelon SC behavior. The SD studies of complex systems dates back to the early work of Forrester (1958) on a systems-thinking approach and followed by John Sterman (2000) where their work has been applied to analyze different aspects such as the analysis of SC disruptions. A profound understanding of the SC and modelling techniques is necessary for modelling a multi-echelon SC (Chilmon and Tipi 2020). SD studies usually focus on causal loop diagrams and control theoretic aspects.

The research around the use of SD simulation to study SC disruptions and assess SC resiliency is diverse. The multi-echelon SD study of Pierreval et al. (2007) is applied to the automotive industry. They highlight that long- or medium-term decisions need a macroscopic or system lens view i.e. systems thinking view. Udenio et al. (2015) develop a SD model for analyzing bullwhip effects for different SC settings and apply their model to a major chemical company. The SD structure allows to track each of these components continuously. The authors conclude that destocking during a crisis enhances demand amplification. Jaenichen et al. (2021) develop a SD model of semiconductor manufacturer to understand the dynamics caused by an end market disruption. The authors highlighted that strong demand dynamics could lead to substantial operational consequences.

The application of simulation methods focused on supply chain resilience is very limited, especially within the semiconductor industry. Theoretical background is, on the other hand, very extensive in literature. Although it is really important and acts as foundation for quantitative analyses, measuring Supply Chain resilience is a vital managerial task as it enhances a company's disruptions management and the identification of improvement needs (Hohenstein et al. 2015).

Chen et al. (2017) develops a simulation model to evaluate how 4 different options of alternative semiconductor manufacturing sites, each with different characteristics, are impacted by different disruptions. The work is intended to support on the determination of alternative manufacturing site as each of them have different times to respond to a disruption as well as different costs.

Wen Jun Tan et al. (2020) developed a simulation model joining discrete event and agent-based approaches for supply chain resilience focused on after disruptions recovery. It discusses and evaluates some mitigation and contingence measures in order to reduce recovery time and recovery costs. As a base for the simulation, a graph model of network structure is used. The main identified result was the improvement of the recovery process through reduction of accumulated backorders and an increase in the rate of backorders fulfilment.

Macdonald et al. (2018) developed a framework aimed at helping researchers build better theories concerning supply chain disruptions. The framework encompasses 3 components: shock nature, supply chain ecosystem and investments in resilience. Additionally, a discrete-event simulations of supply chains with three echelons (supplier, manufacturer, customer) is created in which shocks that interrupt the flow of goods are incorporated. The model is driven by three factors (shock interarrival time, connectivity, and buffer stocks) and captures the impact on the system using 3 measures related to inventory and an additional one measuring the overall system resilience. The framework identifies the elements to be analyzed by simulation, and the simulation in turn provides data to analyze and improve the framework.

Recognizing the importance of oil as a critical energy resource in China, Chen et al. 2020 developed a system dynamics (SD) simulation model to study the resilience of the Chinese oil system against external shocks. The authors use the concept of resilience evolution curve with focus on degradation and recovery. A causal relationship diagram of the system is built based some submodules. Finally, external shock scenarios are simulated and their resilience is calculated in order to evaluate different influencing factors and to help policymakers find better combinations of actions aimed at enhancing the resilience of the system.

In this paper, the methodology developed is restricted to a simulation model using the system dynamics approach. The model is directed to an internal semiconductor manufacturing supply chain and allows for the introduction of different shocks through different parameters. Once disruption scenarios are simulated, an evaluation of the impacts caused to the network can be performed as to identify the vulnerability and resilience levels of the supply chain. The model is further explained in the following section.

3 METHODS

3.1 Simulation Approach

In order to simulate the supply chain resiliency pertaining to external supply chain disruptions, there are three possible modelling methods that can be applied: discrete event, agent-based and systems dynamics (Grigoryev 2021). For this study, system dynamics was chosen as it allows for modelling to be applied for strategic decision making, due its high abstraction levels (Gorigoryev 2021). It allows for complex systems to be modelled in a form of feedback mechanisms and balancing and reinforcing loops. It consists of stocks, flows, dynamic variables, parameters and links to calculate various outcomes. Decisions have various impacts on a system, they can either reinforce the outcome also known as “add to the direction of the loop” or they can balance, which is a counterreaction against the direction of the loop (Grigoryev 2021).

3.2 Simulation Setup

The following subsections explain the system dynamics model’s structure. As depicted in figure 1, it consists of stock and flow structures for each of the supply chain nodes, namely: Frontend Manufacturing, Diebank, Backend, and Distribution Center (DC). Crucial parts such as variables and different disruption events that pose different risks are also explored. The simulation model was developed for the Infineon use case with an underlying conceptual model proposed by Mönch et al. (2018).

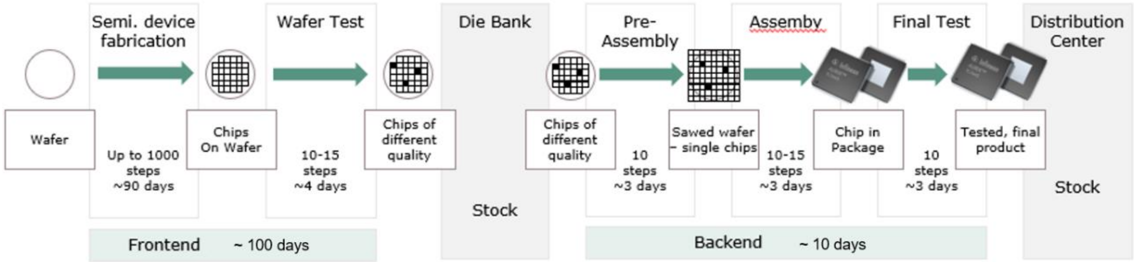

Figure 1: Base structure of the semiconductor manufacturing steps used for the construction of the model.

For every main semiconductor manufacturing step, hereafter referred to as "node", a system dynamics model was created and later connected following the sequence of the whole semiconductor manufacturing process, as per illustrated in Figure 2. Overall, the sequence of events is: customer orders depleting the DC trigger, Frontend production and, material flow through the Diebank and backend until the Distribution Center stock can be replenished.

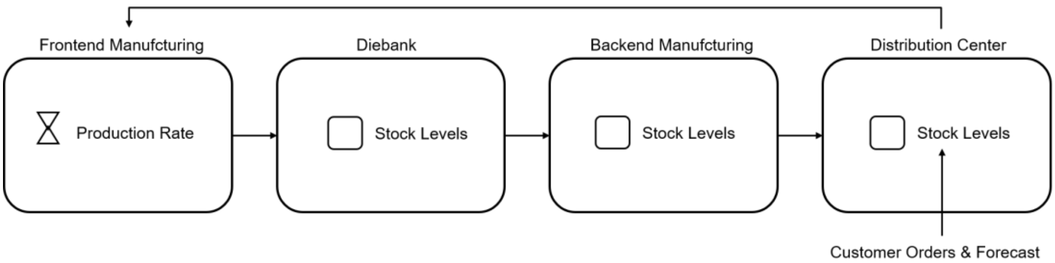

Figure 2: Overview of the semiconductor manufacturing process comprising of its main steps (or nodes).

The logic behind the production trigger is the long lead times associated with the semiconductor supply chain. The following subsection explains the system dynamics model's structure, specifically the stock and flow structures of each of the described supply chain nodes. It is to note that the Distribution Center signifies the usage of a KPI 'Available to Promise' (ATP), meaning that this node has the only stock that signifies the usage of the material by the customer, whereas all other nodes are responsible for the manufacturing of the ATP. ATP signifies the product quantities the firm can commit to its customers, helping customers plan their own production dependent on the semiconductor supply. Crucial parts such as variables and different disruption events that pose different risks are also explained.

Anylogic is a multimethod simulation modeling software that allows for not only system dynamics modelling but also supports agent based and discrete event simulation (Anylogic 2023). The Anylogic software was used to build this simulation use case. The following sections explain all the components of the simulation, namely: Frontend manufacturing, Diebank, Backend manufacturing and the Distribution Center.

Frontend Manufacturing: Frontend manufacturing is the core manufacturing step within the supply chain of a semiconductor. This stage serves as the supply node, where the wafers undergo a series of chemical processes to construct the chip layer by layer onto the wafer.This particular manufacturing phase demands significant time and energy. Thus, when the distribution stock depletes, it is essential to initiate frontend manufacturing to ensure sufficient stock for fulfilling orders. Figure 3 shows the frontend manufacturing system dynamics structure.

The frontend manufacturing step includes a capacity structure. Frontend capacity allows for the addition of new capacity if it were to be added to the frontend manufacturing. This could be, for example, in the form of an expansion of the facility or an increase in equipment, workers and resources. The production start rate is determined by the flows directed to the Frontend node. These are: the capacity and the desired production, signified as "Production_Adjustment_From_DC" in Figure 3, which is triggered from the distribution center order depletion.

In frontend manufacturing, the accumulation of the material stock, signified with "FE_WIP" in Figure 3, is the initial start of production and displays the material to be further processed downstream in the supply chain. The rate of frontend production, which is represented as "Production_Start_Rate" in Figure 3, is triggered from the order rate and depletion in the distribution center. The rate of the work in progress for the frontend manufacturing is an accumulation of how many products are to be started in the frontend process in order to fulfill later orders. The accumulation of the stocks account for their manufacturing times and adjustment times. Once production started, work in progress units accumulates in the "FE_WIP" stock. From there, based to this process' cycle time (parameter "FE_CT"), the materials are released on a rate corresponding to the variable "Outflow_FE". Once released, these units compound the stock "Material_in_Transit" from which they are eventually released on a rate of "Material_Shipment", that depends on the transportation time (variable "Transport_Time").

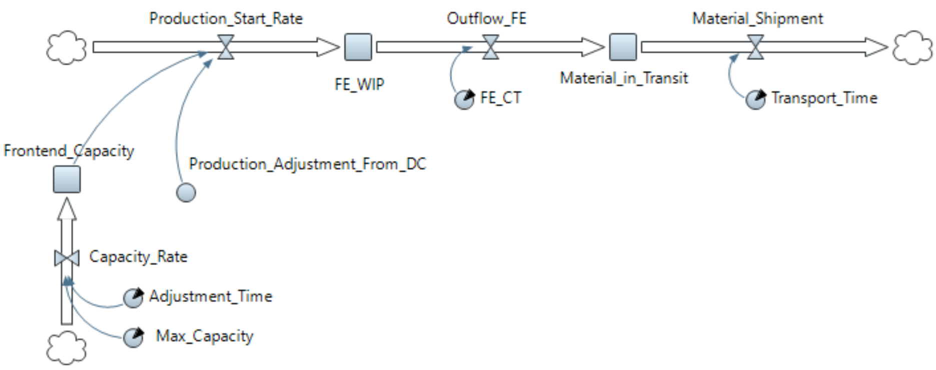

Figure 3: Depiction of the simplified system dynamic structure for the frontend manufacturing node.

Diebank: For the purpose of this model, the Diebank was treated as a location in which the material just stays and waits until it can be shipped again to the next supply chain node, the backend manufacturing. Therefore, it acts as a storage and only accounts for the processing time for the Diebank, signified as "Cycle_Time" in Figure 4. Additionally, the only available stock of the Diebank is the inventory stock named as "DB_Stock", as the model assumes that all of the material that is processed through the Frontend will be shipped to customers, leaving out defect material. However, this structure of the model could be enhanced by the addition of the steps present in a Diebank real structure. Figure 4 shows the Diebank system dynamics structure. The "DB_Stock" considers the accumulation of the material from the frontend, signified as "Material_In_from_FE" as well as safety stock values which are defined with the parameter "Safety_Stock" as seen in Figure 4.

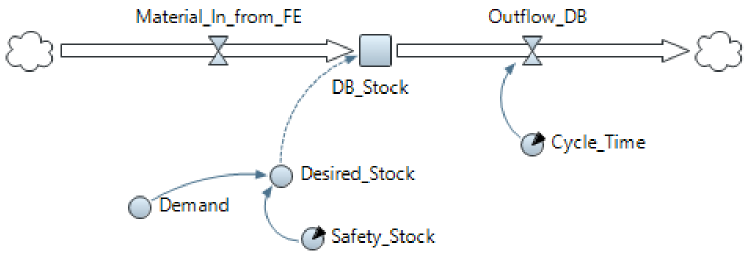

Figure 4: Display of the simplified Diebank system dynamics agent.

Backend Manufacturing: The backend manufacturing structure accounts for the entrance of the material into the backend and for the transport out. As for the Diebank, the Backend manufacturing could also be extended to include balancing structures that realistically occur within it. However, for the purpose of this model it is assumed that 100% of the frontend is processed at the Diebank and at the Backend manufacturing, as the model does not assume defected material as shown in Figure 5.

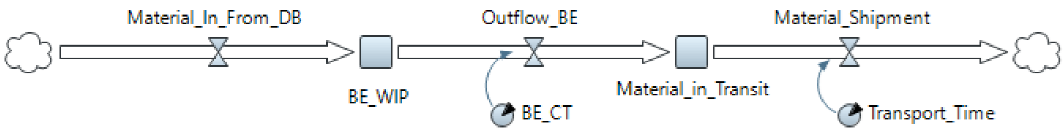

Figure 5: Display of the Backend Manufacturing system dynamics node.

Within the backend there are two major stocks: the work in progress named "BE_WIP" and the stock finalized but not yet shipped, named "Material_in_Transit". This latter stock has been created to include the outflow, representing the transport time to deliver the items to the Distribution Center. The main parameters influencing these flows are the manufacturing time, denoted as "BE_CT" and the transport time.

Distribution Center: The distribution center is the last supply node where the finalized product remains as a stock before being shipped to the customer. The system dynamics structure shown below in figure 6 represents the simplified version of the DC. The depletion of the stock in the Distribution Center is dependent on the customer order rate and the shipment rate. The "Shipment_Rate", as labeled in figure 6, explains the rate of order fulfillment and depletes the "Distribution_Center" stock to deliver material to the customer. The shipment rate is dependent on the target delivery delay, order fulfillment, and "Shipment_Rate_B". When the stock levels reach under a certain level in the Distribution Center, it triggers the production of new products directly in the Frontend.

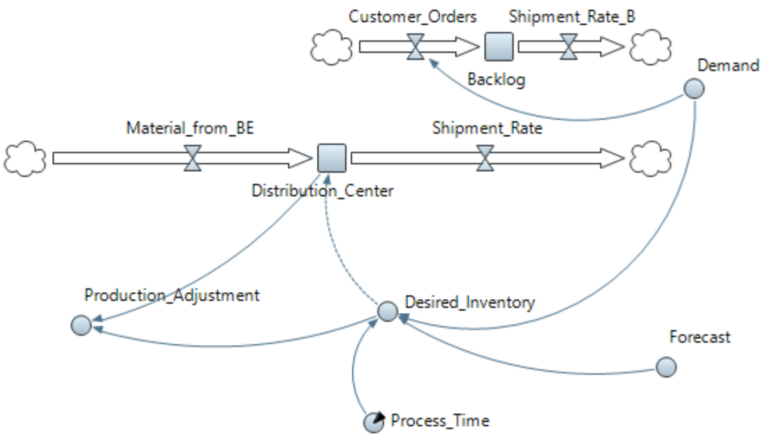

Figure 6: Simplified depiction of the distribution center system dynamics structure.

In order to consider the accumulation of the finalized semiconductor stock from the entire process, it is necessary to contemplate certain flows for the production. The rate at which material enters the distribution center is defined as the "Material _from_BE", which comprises the travel time and the delay from the material out of the backend manufacturing. The shipment rate, which defines order fulfillment, and serves as a basis for ATP, depletes the stock levels. The "Shipment_Rate_B" is a part of the backlog structure and is numerically equal to the "Shipment_Rate". They are different from one another since "Shipment_Rate_B" is an information flow and "Shipment_Rate" is a physical flow (Sterman 2002).

To ensure adequate system dynamics structure, the integration of dynamic variables was used to represent different constants and exogenous inputs (Anylogic 2023). For example, "Desired Inventory", "Demand", and "Forecast" allow for the proper accumulation of the distribution center stock, considering the upstream processes and the balancing processes that occur in the distribution center. The parameters of the DC allow for the characteristics that remain constant in normal functioning to be modeled, for example the process time.

4 SIMULATION RESULTS AND DISCUSSION

Models must demonstrate robustness even in the face of extreme conditions. This indicates that the model should exhibit realistic behavior regardless of the severity of inputs or policies imposed upon it (Sterman 2002). That being so, the model verification was performed through two demand shocks and the consequent analysis of the obtained results. More specifically, the shocks were a steep increase of about 20% in demand right after a stable period as well as a similar decrease in demand also done after a stable period.

The simulation model allows for changes in the parameters as to simulate many different disruptions with the use of different disruption event sliders. Such disruption could be, for example, an increase in transport times due to natural disasters, or it could be a sudden drop in the customer orders due to the disclosure of a major product risk leading to distrust on it. Once a disruption takes place, the user is able to evaluate the resilience level of the supply chain by visualizing the impact that the disruption had on it according to the magnitude in which it changes. More specifically, it is possible to perform a detailed investigation of effects by looking at the stock levels at each node of the network as well as the revenue.

For this paper, a very industry relevant disruption scenario is performed and evaluated as displayed in Figure 7. Such scenario simulates a disruption in which there is initially a reduction in the order rate (highlighted by rectangle ①) followed by some stability and later by a sharp increase (highlighted by rectangle ②), similarly as occurred with the COVID 19 pandemic. This occurrence boosted a dramatic semiconductor shortage worldwide, having an impact on over 169 industries (Howley 2021) and causing revenues losses estimated over USD 100 Billion just in the automotive industry (KPMG, 2021).

The initial demand drop promotes also a drop in DC (highlighted by rectangle ③), as less production is triggered. Afterwards, once demand rises to much higher levels than before the decrease, DC stock suffers a sharp decrease (highlighted by rectangle ④). This can be explained by the fact that the increase in customer orders signals more production and then the ability to fulfill orders. However, since manufacturing times are long, a delay will occur before seeing changes in ATP and stock levels in the distribution center. Therefore, DC stock only recovers some time later (highlighted by rectangle ⑤).

Following a behavior similar to the DC stock, the revenue suffers an initial sharp increase once customer orders drop. That occurs due to a higher order fulfillment as DC stocks are now higher. However, shortly after it already reflects the sales drop and significantly reduces as well and remains stable until the recovery of demand. Once demand recovers, revenue drops again for a while as not enough DC stock is available and thus order fulfillment is low. Finally, when DC stock recovers, revenue recovers as well, reaching levels even higher than in the start of the simulation, as order fulfillment greatly increases. Hence, the main insight that can be derived from that analysis is how such customer order fluctuation, that is, with a sharp increase following a decrease within the semiconductor industry, is hard to recover from. Based on that, strategies to improve resilience could be proposed and evaluated through new simulation runs.

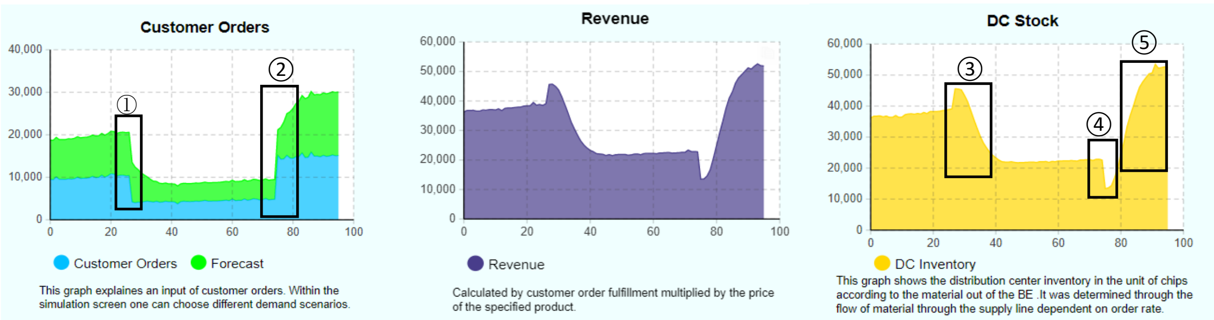

Figure 7: A screenshot of an example result for revenue change in the system dynamics model for the change in customer orders and the projection on the revenue.

Finally, this model can be further used to simulate the impact from diverse shocks in diverse supply chain conditions (parameters) and therefore evaluate how resilient a supply chain is, potentially identifying vulnerabilities and weak points. By running different scenarios and stress-testing the model, it becomes possible to pinpoint areas that are more susceptible to disruptions. Additionally, it enables companies to test and develop effective mitigation strategies and contingency plans to reduce the impact of potential disruptions. Moreover, simulation models provide an ongoing tool for continuous improvement. They can be updated with real-world data, and their insights can be used to optimize supply chain processes continuously.

5 CONCLUSION

To increase supply chain resilience, system dynamics modeling could be used as a guiding hand for management to gain a deeper understanding of the effects that a disruptive event has on a system. It is to be noted that the model does not provide definite value of the change in the different elements monitored such as revenue and stock levels. It rather provides a trend analysis. Disruptive events have and will continue to have impact on supply chains. Given the complexity of the global semiconductor industry supply chain as well as its vitality for other sectors, companies should employ supply chain resilience strategies and testing of what if scenarios through simulation. Simulation results can be used as a tool to make more informed decisions on complex issues.

6 LIMITATIONS AND OUTLOOK

Certain limitations exist when modeling with system dynamics. Since it is a form of mathematical modeling, there are assumptions that need to be considered when trying to simplify the real-world structures.

Disruptive events can be described by both its severity, in the case it happens, as well as by its risk or chance of happening. Especially when simulating, the degree in which the user labels the disruption regarding its severity is dependent on an assumption. Since not all disruptive events are created equally, the user perceives the change in the system at a certain level. However, there may be discrepancies between the actual magnitude of the event to the simulated event. Future models should consider the integration of a range of accuracy in the perception of the events magnitude, showing different levels of confidence.

Moreover, the designed model assumes an infinite and an instantaneous supply of material and equipment, focusing solely on the demand disruption aspect of the supply chain. In case of a sever disruption, such as a natural disaster or a blockade, the material inflow from the suppliers would naturally also be affected, resulting in a reduced or a delayed supply. The model could be improved by incorporating the supply side instead of solely focusing on demand fluctuations, by adding extreme scenarios of supply as a result of disruptions, resulting in more accurate results and a broader outlook.

Finally, another limitation of the model is the simplified structure of the supply chain. Future work could enhance the different system dynamic structures to include more detailed frontend processes, as well as Diebank and Backend structures.

REFERENCES

Anylogic. 2023. Dynamic Variable. https://anylogic.help/anylogic/system-dynamics/dynamic-variable.html, accessed 1st March 2023.

Chen, S., M. Zhang, Y. Ding, and R. Nie. 2020. “Resilience of China's Oil Import System Under External Shocks: A System Dynamics Simulation Analysis.” *Energy Policy* 146: 111795.

Chilmon, B. and N. S. Tipi. (2020). “Modelling and Simulation Considerations for an End-to-End Supply Chain System. *Computers & Industrial Engineering* 150: 106870.

Dolgui, A. and D. Ivanov. 2021. “Ripple Effect and Supply Chain Disruption Management: New Trends and Research Directions”. *International Journal of Production Research* 59(1): 102-109.

Dolgui, A., D. Ivanov, and B. Sokolov. 2018. “Ripple Effect in the Supply Chain: An Analysis and Recent Literature”. *International Journal of Production Research* 56(1-2): 414-430.

Forrester, J. W. 1958. “Industrial Dynamics. A Major Breakthrough for Decision Makers”. *Harvard Business Review* 36(4): 37– 66.

Grigoryev, I. 2022. Anylogic in 3 days. A Quick Course in Simulation Modeling. https://www.anylogic.com/upload/al-in-3-days/anylogic-in-3-days.pdf, accessed 10th June 2023.

Hohenstein, N., E. Feisel, E. Hartmann, and L. Giunipero. 2015. “Research on the Phenomenon of Supply Chain Resilience: A Systematic Review and Paths for Further Investigation”. *International Journal of Physical Distribution & Logistics Management* 45(1/2):90-117.

Howley, D. 2021. These 169 Industries are being Hit by the Global Chip Shortages. https://finance.yahoo.com/news/these-industries-are-hit-hardest-by-the-global-chip-shortage-122854251.html, accessed 26th July 2023.

Ivanov, D., B. Sokolov, and A. Dolgui. 2014.“The Ripple Effect in Supply Chains: Trade-off Efficiency-Flexibility-Resilience in Disruption Management”. *International Journal of Production Research* 52(7):2154–2172.

Macdonald, J. R., C. W. Zobel, S. A. Melnyk, and S. E. Griffis. 2018. “Supply Chain Risk and Resilience: Theory Building Through Structured Experiments and Simulation”. *International Journal of Production Research* 56(12):4337-4355.

Jaenichen, F. M., C. J. Liepold., A. Ismail, C. J. Martens, V. Dörrsam, and H. Ehm. 2021. “Simulating and Evaluating Supply Chain Disruptions Along an End-to-End Semiconductor Automotive Supply Chain” In *2021 Winter Simulation Conference (WSC)*, edited by S. Kim, B. Feng, K. Smith, S. Masoud, Z. Zheng, C. Szabo, and M. Loper, 1-12. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Katsaliaki, K., P. Galetsi, and S. Kumar. 2021. “Supply Chain Disruptions and Resilience: A Major Review and Future Research Agenda”. *Annals of Operations Research* 319(1): 965-1002.

Venture Beat. 2021. KPMG: Car makers will lose $100B in 2021 due to semiconductor shortage. https://venturebeat.com/business/kpmg-car-makers-will-lose-100b-in-2021-due-to-semiconductor-shortage, accessed 20th June 2023.

Llaguno, A., J. Mula, and F. Campuzano-Bolarin. 2022. "State of the Art, Conceptual Framework and Simulation Analysis of the Ripple Effect on Supply Chains". *International Journal of Production Researc*h 60(6): 2044-2066.

Moore, G. 1965. "Cramming More Components onto Integrated Circuits". *Electronics Magazine* 38(8): 114.

Pierreval, H., R. Bruniaux, and C. Caux. 2007. "A Continuous Simulation Approach for Supply Chains in the Automotive Industry". *Simulation Modelling Practice and Theory* 15(2): 185–198.

Mönch, L., J. W. Fowler, and S. J. Mason. 2012. *Production Planning and Control for Semiconductor Wafer Fabrication Facilities: Modeling, Analysis, and Systems*. New York, Heidelberg, Dordrecht and London: Springer.

Ribeiro, J. P., & A. Barbosa-Póvoa. 2019. "Supply Chain Resilience: An Optimisation Model to Identify the Relative Importance of SC Disturbances". In *Operational Research: IO 2018, Aveiro, Portugal, September 5-7*, edited by A. A. Pinto, J. P. Almeida, M. J. Alves, J. F. Oliveira, 189-198. Springer International Publishing.

SafetyCulture. 2023. A Guide to Supply Chain Disruption. https://safetyculture.com/topics/supply-chain-disruption, accessed: 15th April 2023.

Spieske, A., and H. Birkel. 2021. "Improving Supply Chain Resilience Through Industry 4.0: A Systematic Literature Review Under the Impressions of the COVID-19 Pandemic." *Computers & Industrial Engineering* 158: 107452.

Sterman, J. 2000. *Business Dynamics: Systems Thinking and Modeling for a Complex World*. Boston: Irwin/McGraw-Hill.

Tukamuhabwa, B. R., M. Stevenson, J. Busby, and M. Zorzini. 2015. "Supply Chain Resilience: Definition, Review and Theoretical Foundations for Further Study". *International Journal of Production Research* 53(18): 5592-5623.

Udenio, M., J. C. Fransoo, and R. Peels. 2015. "Destocking, the Bullwhip Effect, and the Credit Crisis: Empirical Modeling of Supply Chain Dynamics". *International Journal of Production Economics* 160: 34–46.

Wieland, A., and C. F. Durach. 2021. "Two Perspectives on Supply Chain Resilience". *Journal of Business Logistics* 42(3): 315-322.

Wieteska, G. 2018. "The Domino Effect – Disruption in Supply Chains". *Logforum* 14(4): 495-506.

Tan, W. J., C. Wentong, and A. N. Zhang. 2020. "Structural-aware Simulation Analysis of Supply Chain Resilience". *International Journal of Production Research* 58(17): 5175-5195

Chen, Y., T. Ponsignon, R. Weixlgartner, and H. Ehm. 2017. "Simulating Recovery Strategies to Enhance the Resilience of a Semiconductor Supply Network". In: *2017 Winter Simulation Conference (WSC)*, edited by , V. W. K. Chan, A. D'Ambrogio, G. Zacharewicz, N. Mustafee, G. Wainer, and E. H. Page, 4477-4478. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc..

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