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THE BULLWHIP EFFECT IN END-TO-END SUPPLY CHAINS: THE IMPACT OF REACH-BASED REPLENISHMENT POLICIES WITH A LONG CYCLE TIME SUPPLIER

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ABSTRACT

The bullwhip effect (BWE), a well-known phenomenon in supply chain management since it was first identified in 1958, is causing significant economic damage after disruptions. While the role of human factors in BWE has been widely recognized, however, the impact of different replenishment policies on BWE mitigation has not been thoroughly investigated. This paper presents a study on the impact of reach-based Kanban systems on the BWE in supply chains containing suppliers with intrinsically non-reducible long cycle times, such as those in the semiconductor industry. Our findings suggest that a reach-based replenishment system acts as a BWE accelerator after significant disruptions, which can end up in line downs downstream. We propose a change to absolute stock targets for replenishment policies during disruption to mitigate this aspect of the BWE root cause for supply chain with long cycle time suppliers to reduce the risk of line downs.

1 INTRODUCTION

The bullwhip effect (BWE), as the amplification of demand changes along the Supply Chain (SC), has already been well studied since its demonstration by Forrester (1958). However, the impact of replenishment strategies like reach-based replenishment systems as a possible root cause is, to all our knowledge, not so well researched, and certain replenishment policy adjustments can mitigate this effect. BWE refers to the increasing order variability of the SC upward, posing significant pressure on the upstream suppliers and creating economic inefficiencies due to over- or underproduction (Lee et al. 1997). It is widely known that the semiconductor industry is affected by the BWE, given the insurmountable complexity and variability in both the demand and supply sides (Sterman and Dogan 2015). The production of semiconductors is highly complex, with a long production lead time of more than three months and up to a thousand processing steps in the factories (Ehm et al. 2018). It is thus essential to building a resilient and agile SC management for SCs containing semiconductors, as industries increasingly depend on semiconductors. Demand uncertainties amplified by the BWE should be avoided wherever possible, as they significantly impact other industries. Disruptive events such as the Covid-19 pandemic, the earlier 2008-2009 financial crisis, or the 2000-2001 dot-com bubble, have led in its aftermath to a fundamental shortage in the supply of semiconductors and affected all participants in the end-to-end SC (Udenio et al. 2015; Frieske and Stieler 2022). Even if the original demand changes due to the disruption are difficult to avoid, the BWE amplification should be possible to avoid if the root causes are understood.

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In disruptive situations, understanding long-term structural changes and recovery periods is essential for deciding mitigation strategies (Chopra and Sodhi 2014). However, the recovery path is usually not easily tracked, although the time point of a SC disruption can be readily identified. Some factors may prolong the disruption and induce more BWE with immense demand uncertainty, especially for the automotive semiconductor SC. The severity of a SC disruption is positively correlated with a few factors of the SC structure, including its density, complexity, and node criticality (Craighead et al. 2007). The SC density refers to the cohesiveness of the SC network (Gualandris et al. 2021), while the complexity refers to the inter-connectedness and inter-dependencies in the network (Rienkhemaniyom and Pazhani 2015). These risk factors are often undetected if the SC network is fragmented, like the BWE in the case of the automotive semiconductor SC. Nevertheless, the most concerning factor is the increasing node criticality of semiconductor components in the end-to-end SC of automotive chips, bringing difficulties in both short-term and long-term horizons. In the short term, the consequence of lacking semiconductor components in automotive production is evident during the Covid-19 pandemic. The causes are due to the Just-in-time (JIT) manufacturing model relying on supplies and reduced chip production and logistics capacity. These situations bring many major automobile producers into the production line down situation, referring to the temporary, involuntary production halts due to components or resources unavailability (Wu et al. 2021). On a longer horizon, the growing adoption of electrified vehicles brings a continuing increase in the semiconductor demand. The trend most probably will be further accelerated by the extensive use of artificial intelligence in mobility, such as advanced driver-assistance systems and navigation systems, which will increase the semiconductor components penetration in newly produced vehicles (Boston Consulting Group, Inc. 2022). As a result, the SC disruption in the automotive semiconductor may become a long-term imbalance between demand and supply if the countermeasures fail to manage BWE risk.

Just-in-time replenishment system, such as reach-based replenishment, is ubiquitous in the automotive industry's original equipment manufacturers (OEMs) to maintain an inventory level based on demand (Kros et al. 2006). Moreover, the traditional concept of maintaining customer service level during disruption is to increase the safety stock level, especially when the demand is contingent on many external factors (Beutel and Minner 2012). However, if demand decreases quickly and unexpectedly, excessive inventory builds up at the semiconductor suppliers. Consequently, the short product life-cycle of these semiconductor products leads to a higher risk of inventory scrap. Or, if the production level is adjusted based on current demand signals, the customers may suffer from production line downs due to the shortage of automotive chips. Literature indicates that JIT and reach-based kanban systems can cause BWE during supply chain disruptions with an intrinsic long-cycle time supplier. However, proof by a logical step-by-step argumentation is still missing.

To enhance the transparency of this situation, this paper presents both logical argumentation and an end-to-end SC simulation study. It reveals that the reach-based Kanban replenishment policies under the vendor-managed inventory (VMI) setting accelerates the BWE in SCs with long-cycle time, such as the semiconductor industry after major disruptions. In contrast, if the customers move away from the reach-based replenishment policies during disruption and adopt an absolute stock target, the BWE effect would alleviate. Building on this basis, a more resilient automotive semiconductor SC can create a win-win situation for the automotive (OEM), the Tier1 (the one building systems for the OEM based on semiconductors) and semiconductor industries by largely avoiding production line downs at OEM through reduced demand reductions and fluctuations during disruptions.

The remainder of the paper is organized as follows: Section 2 explains the BWE, Section 3 explains the JIT replenishment principles and that JIT with the VMI system in the automotive semiconductor is a BWE accelerator when setup as a reach-based Kanban system in the SC, as it is the standard mode today. Section 4 presents the simulation implementation, and Section 5 analyzes the results. In the end, Section 6 provides the concluding remarks of this paper.

2 BULLWHIP EFFECT AND THE SEMICONDUCTOR INDUSTRY

The term BWE has been coined by Forrester (1958) and Lee et al. (1997), which describe the increasing variability of demand signals up the SC. Lee et al. (1997) has identified four contributing factors to the BWE: demand updating, order batching, price fluctuation, and rationing game. These factors significantly impact the decision-making process throughout the SC. He describes that although the decisions made are rational, the limited access to information and risk aversion have, among other factors, led to the distortion of demand information. Therefore, BWE is a critical issue in SC decision-making because it resulted in inefficiencies in manufacturing, such as a mismatch between production levels and reduced customer satisfaction.

Various papers examine the drivers of BWE and information distortion using an experimental approach. The analysis of the inventory management game, known as the "Beer game" by Sterman (1989) shows that when information is suboptimal, demand order distortion occurs, and on-order inventory delivery is often neglected. Moreover, the BWE remains significant, even if the actual demand is stationary (Croson et al. 2004). The objective of minimizing the inventory and stockout costs can also result in an irregular ordering pattern, causing the demand signals sent upstream to become less smooth (Wang and Disney 2016).

The BWE is highly relevant in the semiconductor industry, as the upstream position of the semiconductor industry in multiple SCs reduces the information transparency (Bray and Mendelson 2012). The problem amplifies with the complex production environment's long production cycle time and the need for highly specialized components. As a result, having accurate demand forecasts and operational flexibility is a considerable challenge for the semiconductor industry but also rewarding, given good management (Ehm et al. 2011). Therefore, an agile, adaptable, and aligned SC framework is paramount to the continual success in managing the SC (Lee 2004), especially during the disruptive scenarios such as the Covid-19 pandemic in 2020-2022, the financial crisis in 2008-2009 and the dot-com bubble in 2000-2001.

The BWE amplification under disruptive scenarios has also been studied. Udenio et al. (2015) explains the BWE observations after the financial crisis in 2008-09 by modeling the dynamic decision-making behavior of each echelon in a chemical company's SC and showing the amplifying effect of BWE in the upstream suppliers due to destocking. Fransoo and Udenio (2021) extends the investigation to the pandemic and local shutdowns due to Covid-19 and explains the challenges of having excess inventory. Dolgui et al. (2019) explains the impact on inventory level induced by production disruption, and a simulation has been built to show the importance of suppliers and customers coordination in tackling BWE. For example, redundant order allocations from customers overload the SC when the information from the suppliers on the reduced production level lacks transparency. There are also researches in the semiconductor industry, for example Jaenichen et al. (2021) and Diaz et al. (2022), evaluating the BWE under disruption with simulation approaches and outlining that clear, unbiased communication of demand information is the key to alleviating the BWE.

This paper postulates the hypothesis that a reach-based Kanban system caused the BWE right after disruption and can cause production line down in downstream manufacturers, like the OEM, when one supplier in the upstream SC has an intrinsic long production time, like a semiconductor company. However, research addressing this hypothesis that a reach-based Kanban system for inventory replenishment can be a BWE driver in the Semiconductor industry, SC of OEM during disruption and causing line down at OEMs is lacking. Therefore, this article will use logical arguments and a simulation approach to show the linkage between reach-based replenishment and BWE.

3 REACH-BASED REPLENISHMENT POLICIES AND VENDOR-MANAGED INVENTORY

3.1 Replenishment in the Automotive Industry: Just-in-time and Reach-based Concept

JIT manufacturing is a global cornerstone of the automotive industry's processes. Originating from the famous Toyota Production System by automobile manufacturer Toyota (Monden 2011), JIT manufacturing concerns the fine calculation of the number of raw materials and parts in the manufacturing processes to minimize the work-in-progress and product cycle time of the OEM and/or the Tier1 (Turnbull 2007). The pull approach of JIT manufacturing reduces the inventory level in the production environment, and replenishment is only closely connected according to current demand changes instead of the forecasted demand (Hou et al. 2011). JIT typically enhances production efficiency in multiple ways, such as reducing lot sizes, minimizing rework and waste, and increasing process yield (Hou et al. 2011).

The JIT concept appears in different forms in automotive manufacturing and often impacts inventory replenishment policies. A widely established measure of inventory level is the "Stock Reach," defined by the current stock level over the stock demand in a period (Caplice and Sheffi 1994). The maximum and minimum stock reach are either mutually agreed upon between supplier and customer or are calculated to avoid a stock out (minimum target level) in normal business fluctuation and to keep the inventory target on an acceptable level. A replenishment order is triggered automatically if the inventory level falls below the minimum reach target (Ehm et al. 2018). This benchmark is usually helpful in monitoring inventory flow and ensuring the financial viability of the current operations (Jatta 2016). JIT at the multi-SC level is often introduced as a Kanban system. The lean system forms triggering signals to control inventory levels (Lage Junior and Godinho Filho 2010), as the entire manufacturing has been synchronized with the current customer demand (Agus and Hajinoor 2012) during "normal" business fluctuation periods. The method decides the proper number of components and materials to be ordered and utilized at the right time so that the system works effectively under various production and market conditions. The Kanban system connects the production stages and operations to eliminate overproduction (Thürer et al. 2019).

Our hypothesis, supported by literature review, is that these JIT-based concepts with a reach-based Kanban system for inventory management have disadvantages, especially under disruptive conditions. Let us take Tier1, where the JIT concept depends highly on supplier material delivery (semiconductors), and any needed delivery will significantly impact production efficiency at the customer (OEM) (Xu and Chen 2016). Krishnamurthy et al. (2004) states that Pull-based strategies may not function well under stressed situations with high customer demand. Service levels and back-order delays are sensitive to the optimal allocation for each product. To mitigate these problems, long-term strategic partnerships with core suppliers are a pre-requisite of lean manufacturing to reduce the disruption risk (Othman et al. 2016), and the frequent exchange of actual demand and inventory information without shortage gaming is of the highest importance in maintaining these partnerships.

3.2 Vendor-managed Inventory in the Semiconductor Industry

The VMI system is the usual IT-implemented automotive-Tier1 Semiconductor SC collaboration model. The system is intended to give the suppliers the responsibility of making inventory replenishment decisions in terms of timing and quantities (Southard and Swenseth 2008), and it is usually implemented automatically via the IT system continuously. For SC with suppliers with suppliers with intrinsic long cycle times, VMI is commonplace as the inventory replenishment rules need to be agreed between the stakeholders involved. An illustration of the VMI setup is shown in Figure 1. The VMI model strongly relies on the partnership intent between customers and suppliers to match demand and supply closely (Angulo et al. 2004). Suppliers observe the stock level in the VMI system, and customers can directly pull from the warehouse without placing an order (Ehm et al. 2018). Furthermore, the warehouse location is usually near the customers' sites, offering flexibility to the customers (Claassen and Van Raaij 2008). VMI has been widely adopted in the industry, as the setup usually improves information sharing and customer service levels (Simchi-Levi et al. 2021). By planning these activities in advance, suppliers can save production, logistics and inventory costs (Marques et al. 2010).

The VMI system relies principally on either the mutually agreed stock reach levels, and thus proper parameter selection benefits both parties (Fry et al. 2001). Nevertheless, VMI violations often come with challenges under uncertain market conditions. Typical VMI violations can be grouped into three categories with increasing severity: overstock (beyond maximum zone), understock (below minimum zone), and stockouts. These VMI violations often happen when demand variance grows or when the gap between

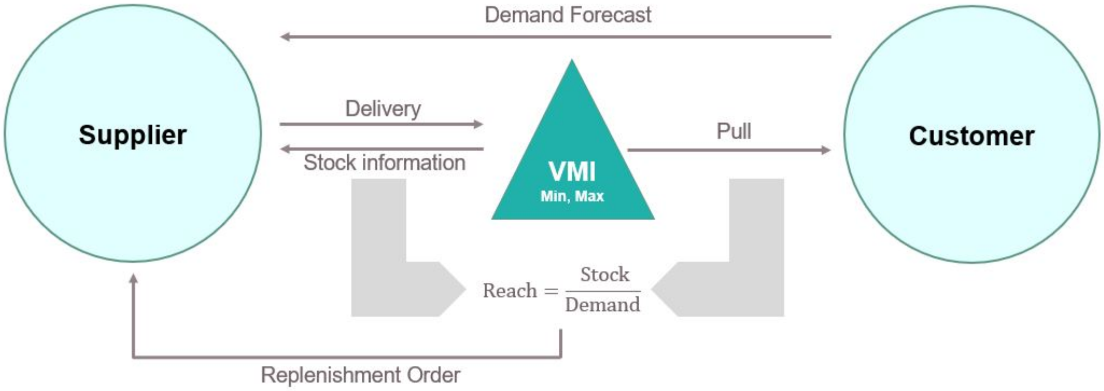

Figure 1: Illustration of a typical VMI setting, adapted from Ehm et al. (2018).

actual and forecasted demand is significant. There are also some discussions on developing an integrative performance measurement framework, for example, to assign some responsibilities to the customers (when the forecast accuracy is below the agreed forecast accuracy), such that customers are encouraged to provide accurate forecasts to maintain the clarity and resilience of the VMI system (Ehm et al. 2018).

3.3 Reach-based Replenishment Policies as a Natural BWE Amplifier

Our hypothesis that reach-based replenishment policies lead to BWE acceleration is now explained via several means a short overall logical explanation, a graph-based visualization, and a simulation. For the logical explanation, the following example will serve: When demand is halved, the stock reach will be doubled, leading to a few weeks without replenishment, when the target minimum stock level was set as a reach-based target. SC with suppliers have already recognized this problem with intrinsic long cycle times, and thus forecast has been used for replenishment (Ehm et al. 2018). However, the reach-based replenishment policies are still an accelerator of BWE when the capacities and deliveries are used for other customers when the demand from the OEM is missing for a longer time, as happens during disruptions.

For the graph-based visualization: A simple graphical scenario is presented in this section to illustrate the replenishment behavior under disruptive demand changes. The Stock Reach level is the fraction of the inventory level and the current demand. Therefore, if a graph places current demand on the x-axis and inventory level on the y-axis, the slope can represent the stock reach level.

Figure 2 shows the situation of an unexpected demand shock in the VMI system using a reach-based replenishment policy. In this case, the desired inventory level is 600 units, based on the original demand of 200 units, a target stock reach of 3 weeks, and weekly replenishment. If there is a 50 % demand decrease to 100 units per week, the inventory status shifts to the left, and the inventory status moves to point 1 $(100, 500)$. As the new stock reach on weekly demand is $500/100 = 5$, replenishment will not be needed at the same demand level until the inventory status reaches point 4 $(100, 200)$ in the graph.

An abrupt demand increase also presents a challenging situation, especially when the production capabilities have been moved to other areas with higher demand. Figure 3 shows the impact of an unexpected demand from 100 units per week to 200 per week (100 % increase). As more inventory is pulled, the inventory status drops to point E $(200, 100)$. The new demand level requires an inventory stats of point 1 $(200, 600)$ after the replenishment, leading to a sizeable 500-unit replenishment for that week. Therefore, from these two simple scenarios, reach-based replenishment policies amplify the BWE.

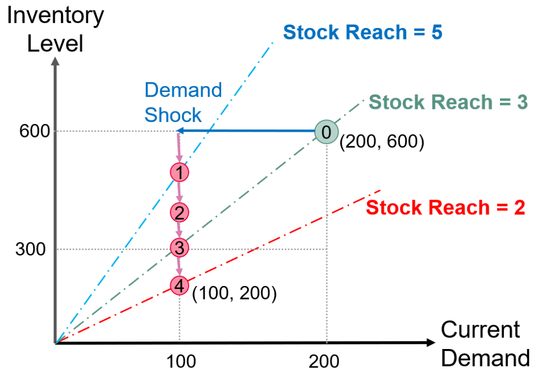

Figure 2: Negative demand shock with reach-based replenishment leads to prolonged replenishment stop. Not to scale.

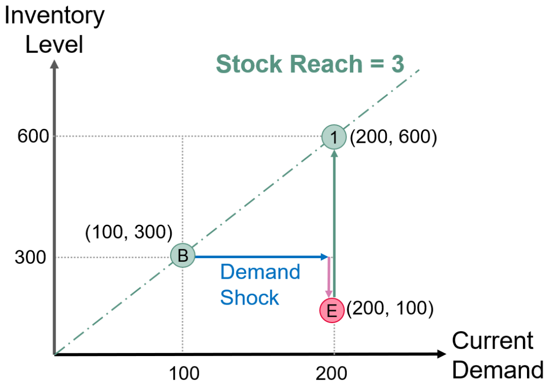

Figure 3: Positive demand shock with reach-based replenishment leads to an abrupt increase of inventory replenishment. Not to scale.

4 SIMULATION OF BWE WITH A LONG-CYCLE TIME SUPPLIER WITH REACH-BASED REPLENISHMENT

A simulation model (Kar Chowdhury, S. and Ehm, H. and Ismail, A. 2023) has been created to model the automotive semiconductor SC. The simulation-based explanation demonstrates the time delayed effect from the intrinsic long-cycle time of a semiconductor supplier to the OEM, as the non-reducible long cycle time extending to the customer side. This causes line down there according to demand signal amplification by the reach-based Kanban system during disruption. This section thoroughly explains replenishment policies under disruptive scenarios using a simulation approach in an automotive semiconductor SC.

4.1 Parameters and Mathematical Relations

The VMI's key parameters and mathematical relations are first introduced to bring a clear modeling foundation. Under a typical VMI setup, the supplier replenishes the inventory to maintain a pre-agreed target reach level (TR), for instance, a ten-week reach. As the target reach level often depends on the SC strategies and production capacities accordingly, and the effect we demonstrate increased with a low target level, a higher target level has been chosen. Furthermore, lot size is often neglected in the literature, where a lot size introduction would likely further amplify the effect. Given a current weekly demand (D_i), the desired inventory level (DS_i) is simply a multiple of both:

$$DS_i = D_i \times TR.$$

Based on the VMI level at the end of the week ($VMIS_i$), the replenishment (SDC_i) from the supplier is defined as follows:

$$SDC_i = max(DS_i - VMIS_i, 0).$$

Therefore, the actual stock reach level (R_i) can be calculated at every time instance as follows:

$$R_i = \frac{VMIS_i}{D_i}.$$

Moreover, production capacity is modelled by the demand signal received from the customers, including semiconductor production. Assuming a maximum feasible production capacity (C), the automotive chips production level at the time i (SSD_i) is based on the following:

$$SSD_i = \begin{cases} C & \text{if } TR > R_i \text{ } and \text{ } D_i > C \\ D_i & \text{if } TR > R_i \text{ } and \text{ } D_i < C \\ 0 & \text{otherwise.} \end{cases}$$

4.2 Simulation Model and System Flow

The simulation is based on the automotive semiconductor SC, shown in Figure 4, from the semiconductor factory to the OEM customers, with a continuous time scale of 70 weeks. The element "Prod" in the semiconductor supplier refers to the production process, from the demand planning stage to finished products. The semiconductor production cycle time (PCT) for Frontend and Backend is assumed to be 20 weeks. After that, the products are delivered to distribution centers (DC). Therefore, the product flow component (SS_i) from Semi Prod to DCs is represented by a first-order delay component $delay(SSD_i, PCT)$. After the products arrive at the DC, the products are sent to the VMI warehouse based on the replenishment need of Tier 1, and the flow is represented by the component (SDC_i). A further assumption is that if the replenishment SDC_i needed is less than SS_i, the products will be diverted to a non-OEM customer with the flow of SO_i, which is modeled by the formula $SO_i = max(SS_i - SSD_i, 0)$. Moreover, the simulation assumes that all products that flow from the VMI system to the Tier 1 supplier are used by the OEM directly. Therefore, the outgoing flow from the VMI is the OEM's demand (D_i).

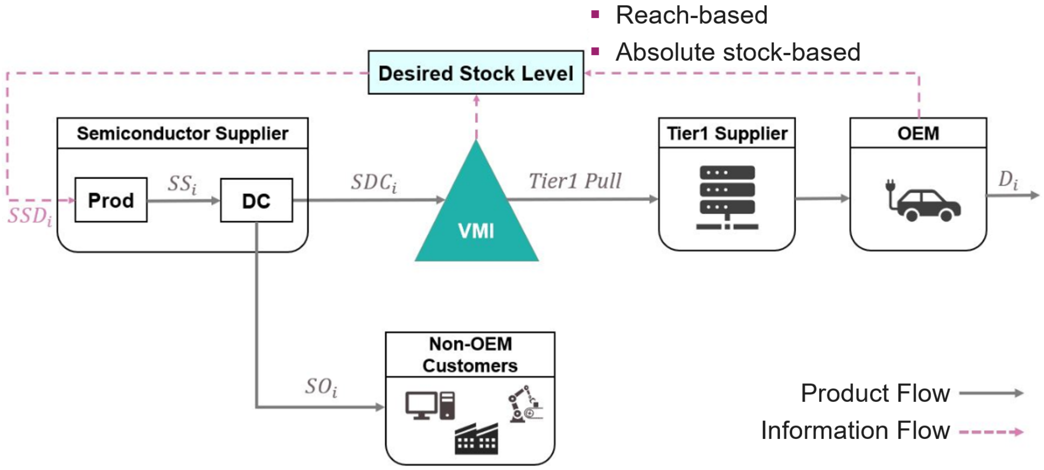

Figure 4: Layout of the system dynamics simulation model of automotive semiconductor SC

Under a reach-based replenishment policy, the target reach level (TR) determines the desired stock level. As an alternative case, another model with an absolute stock level-based target has been created. The absolute stock-based model assumes that the suppliers and customers agree to maintain a fixed desired stock level (DS) instead of a reach-based one. All assumptions and parameters remain the same otherwise. Therefore, the automotive chips production level at time i (SSD'_i) is altered as follows:

$$SSD'_i = \begin{cases} C & \text{if } VMIS_i < DS \text{ } and \text{ } D_i > C \\ D_i & \text{if } VMIS_i < DS \text{ } and \text{ } D_i < C \\ 0 & \text{otherwise.} \end{cases}$$

By considering interrelations of objects at a higher aggregation and using causal loop diagrams, System Dynamics models are useful to drive insights on strategies (Sterman 2000). Similar researches to analyze BWE on the end-to-end SC level have also used system dynamics models extensively, such as Udenio et al.

(2015) and Olivares-Aguila and ElMaraghy (2021), and show clear benefits in capturing the behaviour of the whole system and drawing strategic insights.

5 RESULTS OF THE SIMULATION RUNS

Both variants (the "Target reach-based Kanban System" model and the "absolute Stock right after disruption starts" model) of the model are run with identical OEM demand signals. The length of a simulation run is 70 weeks. A start-up of 40 weeks is needed for initiating the model, which the data collected at the start-up process is removed. Starting with an initial demand of 100 units per week, the first demand shock at week 10 reduces the demand to 50 units. After that, the second demand shock at week 40 increases the demand to 150 units. Despite the generic nature of this example, this setup is analogous to the situation at the start of the corona pandemic in March 2020. The shifted capacities afterward (e.g. shifted capacities from Silicon Foundries) was very complex, with long-lasting production line downs. This is not in the scope of this paper.

Figure 5 compare the production level (SSD_i or SSD_i') of the automotive chip at the semiconductor factory, for reach-based and stock-based models under the same OEM's demand signals. The blue line is the signal sent to semiconductor production. When the OEM demand drops by 50 %, it leads to a production line down of automotive semiconductors for around seven weeks ($R_i > TR$) before recovering to the new demand level. In comparison, for the absolute stock-based replenishment, the signal for semiconductor production is still equal to the end market demand.

Figures 6 and 7 show the product flows in the reach-based and stock based systems respectively after the simulation run. An observation is on the demand signals to DC, which have a 20-week phase lag due to the production cycle time between the semiconductor production and DC. In Figure 6, when the demand signal falls in week 10, the flow between DC to VMI (SDC_i) decreases to zero for a few weeks, as replenishment is not needed until actual stock reach falls below target reach level after the disruption. However, the incoming product flowing to DC (SS_i) from Semi Prod remains, as the production level has already been decided 20 weeks ago. Therefore, the incoming flow continues even if the current production signal (SSD_i) is zero. The incoming products are not stored in DC but sent to the alternative non-OEM customers since there is no demand signal from the automotive customer at the moment. Meanwhile, the customer continues to pull stock from VMI based on the reduced current demand (D_i), and the need can already be satisfied by the existing products in VMI. As a result of zero production signal (SSD_i) starting from week 10, finished product entering DC falls to zero at week 30. However, as stock are not stored in the DC, the products flow from DC to VMI (SDC_i) also drops further below the desired VMI level.

The stock-based model's flow from DC to VMI (SDC_i) drops to 50, along with the customer demand (D_i) in week 10. Due to the phase lag, the flow between the semiconductor production and DC (SS_i)

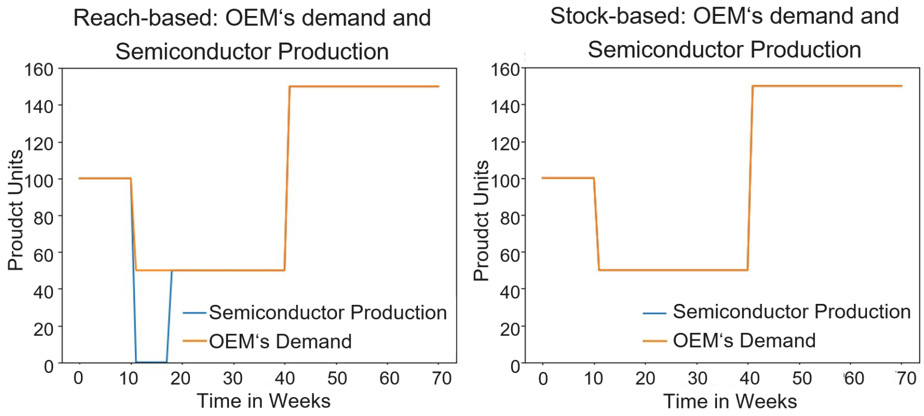

Figure 5: Demand signals in the reach-based simulation (left) and stock-based simulation (right).

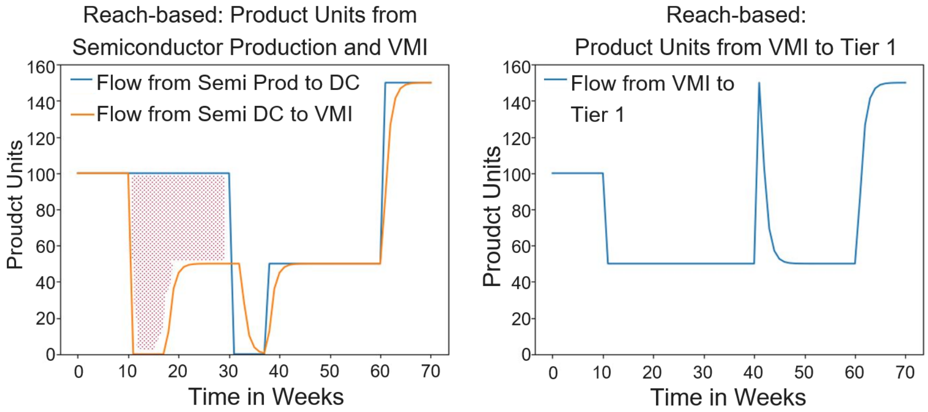

Figure 6: Flow between semiconductor production and Tier1 in the reach-based simulation. The dotted area refers to the products sent to non-OEM customers.

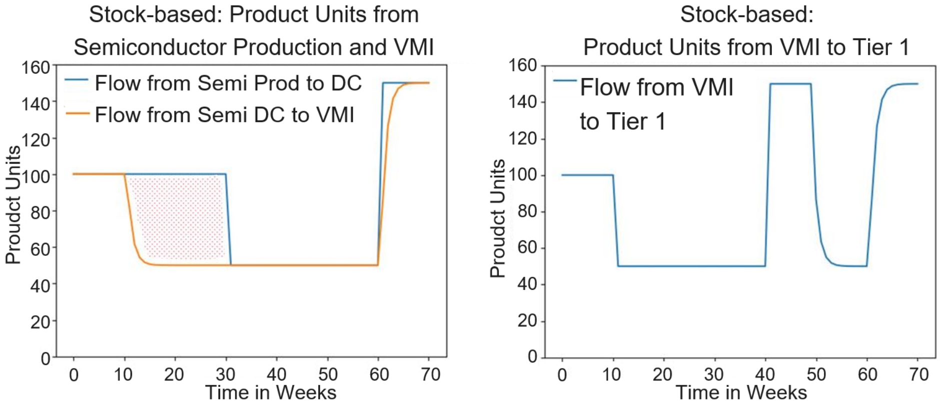

Figure 7: Flow between semiconductor production and Tier1 in the absolute stock-based simulation. The dotted area refers to the products sent to non-OEM customers.

drops to this level after 20 weeks. The excess products sent to DC between weeks 10 and 30 are sent to non-OEM customers. When the demand increases abruptly to 150 in week 40, only 50 units per week can be sent into the VMI (SDC_i) based on the production level 20 weeks ago. As the remaining stock is previously transferred to non-OEM customers at DC, VMI depletes quickly in the reach-based simulation. In contrast, the depletion of VMI stock happens at a later stage for the absolute stock-based simulation.

Figure 8 compares the VMI levels for the two simulation models. Absolute stock-based (right after disruption happens) simulation shows better results in managing the two demand disruptions. When demand drops at week 10, the VMI stock maintains a constant level with the absolute stock-based policy, which has a less disruptive effect than the VMI drops due to distorted demand signals with the reach-based policy. When demand increases at week 40, the absolute stock-based policy can alleviate the stockout condition, resulting in a lower backlog stock.

Overall, these results have shown that the three components of BWE, namely amplification, oscillation and phase lag (Sterman 2000), are reinforced due to the target reach-based replenishment policies. By identifying and removing the target reach-based Kanban system as a BWE cause and replacing it by an absolute stock-based system at disruption, an end-to-end SC with a long-cycle time supplier can manage the disruption risk better, and avoid economic losses due to SC-induced production line downs.

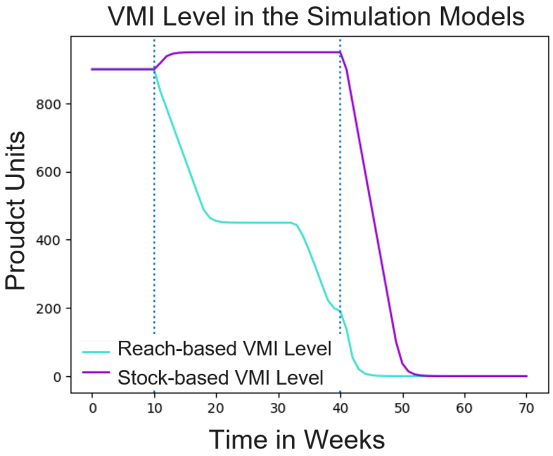

Figure 8: Comparison of VMI Levels in the simulations.

6 CONCLUSION

This paper uses a simulation approach under disruptive scenarios to explain how the target reach-based Kanban replenishment policy amplifies BWE on a SC with a long cycle time supplier. Firstly, we explained the definition of a target reach-based replenishment policy, the VMI structure in the semiconductor industry, and why reach-based replenishment targets naturally induce BWE at disruptions. After that, a system dynamics simulation of the automotive semiconductor SC was built and showed that reach-based replenishment amplified the BWE during SC disruptions significantly, compared with absolute stock-based replenishment introduced when disruption happens. However, reach-based replenishment led to no replenishment over a few weeks and thus stopped production at OEM. Due to missing demand signals, it also leads to deliveries (and midterm capacity allocation) used for non-OEM customers. Moreover, this "delayed" and amplified demand signal affects a long-cycle time supplier's deliveries, replenishment strategies (and capacity allocation). On the other hand, if the replenishment had followed an absolute stock level target right at disruption, the simulation has shown that the demand signals are passed without being amplified by the BWE. Therefore, to build resilient inventory replenishment strategies, moving away from reach-based replenishment targets at disruptions towards time-limited absolute stock levels helps to avoid BWE amplification in IT-implemented replenishment systems and avoids line down.

The development of the simulation approach has opened up new areas of future research. For example, a possible research area is the exact time points for switching from a reach-based replenishment policy to an absolute stock-based one. Moreover, this simulation provides a good starting point for examining other replenishment policies, such as forecast-based policies. There is currently also research on forecasting VMI stock levels using statistical or machine-learning methods. Consequently, the relationship between the inventory level and internal and external factors is better understood. A Hypothesis is that a pure forecast-driven target may bring more flexibility to the inventory replenishment system, which also helps during disruptions. Furthermore, the current simulation can be further enhanced by considering the ordering behavior, shortage gaming situations, and asymmetric information. The cooperative structure between suppliers and customers in a SC with a long cycle time supplier can be further analyzed.

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