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Closed-loop supply chain simulation with disruption considerations: A case-study on Tesla

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Abstract

Performance impact of severe disruptions in the reverse part of an automotive closed-loop supply chain is studied with the use of a discrete-event simulation model implemented in anyLogistix software. A hybrid case study-simulation methodology is applied in this research to analyze the six-echelon closed-loop supply chain of Tesla from positions of resilience. Based on the secondary data, an example for the German market has been created and investigated. More specifically, the results help to show how a disruption in the reverse supply chain may affect the financial and operational performances of the company. Different recovery policies have been simulated in order to analyze how each might recover the supply chain from disruption and restore its operation and performance.

Keywords: closed-loop supply chain; resilience; simulation; anyLogistix; disruption; case-study; performance; e-mobility; reverse logistics

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Dr. habil. Dr. Dmitry Ivanov is Professor of Supply Chain Management at Berlin School of Economics and Law (BSEL). His research explores supply chain structure dynamics and control, with an emphasis on global supply chain design with disruption consideration, distribution planning, and dynamic (re)-scheduling. He is (co)-author of structure dynamics control method for supply chain management. He gained his PhD (Dr.rer.pol.), Doctor of Science (ScD), and Habilitation degrees in 2006 (TU Chemnitz), 2008 (FINEC St. Petersburg), and 2011 (TU Chemnitz) respectively. In 2005, he was awarded a German Chancellor Scholarship. He is the (co)-author of more than 260 publications. Professor Ivanov’s research has been published more than 50 papers in prestigious academic journals. He is Chair of IFAC TC 5.2 “Manufacturing Modelling for Management and Control”.

Dr. Daria Battini is Associate Professor of Industrial Systems and Logistics at the University of Padova (Italy). The principal topics covered by her researches are: industrial system design and management (in particular flexible assembly systems), supply network mapping, modeling and optimization with particular attention to Closed Loop Supply Chains, ergonomics in material handling and in assembly, the inventory management and product/process traceability. Her researches are published in several international journals, international conference proceedings, trade magazines, industry reports and newspapers. She published more than 60 scientific papers, published in International ISI and Scopus journals. She is a member of IFAC and Euroma.
1. Introduction

We study the impact of severe disruptions (i.e., random events that may affect the structural dynamics of a system such as natural and man-made catastrophes, strikes or political crisis) on supply chain (SC) performance in an automotive closed-loop SC (CLSC). More specifically, the objective and contribution of this study is to develop an approach to analyse the disruptions in the reverse part of the CLSC (e.g., a temporary unavailability of a warehouse for collecting the used batteries for electric cars) in regard to (i) their impact on overall SC performance as well as to (ii) proactive and reactive policies with considerations of inventory control policies and sustainable manufacturing concepts.

Inventory management has been evolving over last decade with an ever increasing consideration of sustainability factors and CLSC management (Govindan et al. 2015, Heydari et al. 2017, Jeihoonian et al. 2017, Basiri and Heydari 2017). However, the inventory control policies subject to disruptions in the reverse part of the CLSC have rarely been analysed. Such an analysis appears to be an important contribution to the sustainable inventory management domain since the resilience of the reverse CLSC part is tightly interrelated with the sustainable inventory management and SC sustainability in general (Rezapour et al. 2015, Feng et al. 2017, Heydari et al. 2017).

Since the beginning of the industrial development, companies considered the possibility of reusing and recycling parts of products or materials for efficiency increase. At the beginning, this concept only at a small scale for high-value and low-volume products such as railway industry was used (Guide and Van Wassenhove, 2009). Recently, the importance of managing the closed-loop material flows has been given increasing consideration for three main reasons: First, the need to satisfy the requirements imposed by the legislations; second, many firms realised the strong positive economic effects that could be realized as a result of recycling and reusing oppor-
tunities; finally, companies exploited the customers’ concern for the environment, aiming to improve their public image to gain a competitive advantage (Jeong-Eun & Kang-Dae, 2013, Choi 2013, Yuan et al. 2015, Ivanov et al. 2017a).

Following the literature analysis, it becomes evident that the forward and reverse SCs need to be designed and analysed simultaneously to maximize the company benefits (Zhou et al. 2017). This need for integration becomes more critical because of the competitiveness of the actual environment where the organization must deal with high fluctuations in the demand to assure customer satisfaction at a high level of costs efficiency (Hasani et al. 2012).

Along with the demand uncertainty which is typically referred to in literature as recurrent or operational risks (Tang 2006, Chopra et al. 2007, Klibi et al. 2010, Fahimnia et al. 2016, Ivanov 2017), uncertainty and risks of severe disruptions such as explosions, fires, tsunami, strikes or political crises have recently appeared in literature as a crucial research avenue to improve SC resilience (Ivanov et al. 2014, Ambulkar et al. 2015, Snyder et al. 2016). Disruption risks have been extensively investigated in regard to SC performance analysis of different disruptions, proactive and reactive policies (Ivanov et al. 2017c) whereby simulation analysis has been recognized as a useful tool to model disruption and recovery SC dynamics (Carvalho et al. 2012, Schmitt and Singh 2012, Ivanov 2017). However, disruption analysis in the reverse parts of CLSCs still represents a research gap.

In regard to the contribution to the existing literature, this is the first study that applies discrete-event simulation methodology to analyze disruptions in the reverse part of a CLSC. More specifically, the temporary unavailability of a warehouse for collecting used batteries for electric cars is considered. The impact of this disruption is analysed in regard to overall SC operational, financial, and customer performance. Subsequently, proactive and reactive policies with consider-
ations of inventory control policies and sustainable manufacturing concepts are simulated and managerial insights are derived.

The rest of this paper is organized as follows. In Sect. 2, literature analysis is performed. The case-study and problem statement are described in Sect. 3. In Sect. 4, the conceptual simulation model is presented. Sect. 5 comprises experimental simulation results and their managerial analysis. We conclude the paper in Sect. 6 by outlining the main insights and future research needs.

2. State-of-the art analysis

We start the literature review analysis with recent simulation studies with disruption considerations. A disruption may be defined as an unplanned and unanticipated event that can disrupt the normal flows of activities and products along the SC and that can cause stockouts, customer dissatisfaction and great financial losses for all the members of the SC (Spiegler et al. 2012, Ivanov et al. 2017a).

Severe disruptions can be characterized by three important dimensions of analysis, i.e., magnitude, duration, and frequency. Compared to the bullwhip effect, which is associated with high frequency/low impact disruptions, severe disruptions are associated with low frequency/high impact profiles and present new challenges for the SC managers (Ivanov 2017). This complexity increases with the range and intensity of the disruption (Świerczek, 2013).

Carvalho et al. (2012) analyse a four-stage automotive SC. They focus on recovery strategy influences on the SC performance in the case of disruptions. The performance impact has been analysed in regard to lead-time ration and total SC costs using an ARENA-based simulation model. Schmitt and Singh (2012) modelled proactive and recovery strategies that include satisfying demand from an alternate location in the network, procuring material or transportation from an alternative source or route, and holding strategic inventory reserves throughout the SC.
The authors reveal a dependence on employment efficiency of back-up mitigation methods on the response speed.

Lewis et al. (2013) analyse the disruption risks at ports of entry with the help of closure likelihood and duration which are modelled using a completely observed, exogenous Markov chain. They study a periodic review inventory control model that for studied scenarios indicates that operating margins may decrease 10% for reasonably long port-of-entry closures or eliminated completely without contingency plans, and that expected holding and penalty costs may increase 20% for anticipated increases in port-of-entry utilization. Hishamuddin et al. (2015) simulate a three-echelon inventory system in the SC with multiple sourcing and consider both supply and transportation disruptions. They include disruption duration, recovery costs, and a random disruption generator in the model. The most important finding of this study is that back-order quantity and recovery duration have strong positive correlations with total SC costs as compared to the importance of lost sales.

In analyzing disruptions in the reverse SCs, it is important to understand the structural and financial aspects influencing this domain. According to the study by Giuntini & Gaudette (2003), the average cost of collecting and remanufacturing a product is typically 40-60% of the cost of a brand-new product. Large retailers, such as Home Depot, could have return rates of 10% of sales or higher, with total values of returns that run around hundreds of millions of dollars for a single retailer (Guide & Van Wassenhove, 2009).

In regard to structural CLSC design, the use of the logistics consolidation centers has been discussed in the study by Kaynak et al. (2014). The consolidation centers aim at creating a centralized, coordinated, and integrated network for both the forward and reverse flows. Hasani et al. (2012) and Choi (2016) point out that the creation of an agile and resilient CLSC helps to im-
prove the flexibility, adaptability and quick response to utilize the emerging opportunities in the market. A similar concept is extremely important regarding the design of resilient SCs when considering severe disruption risks in the reverse flows (Ivanov et al. 2017b). At the same time, analysis of both CLSCs and disruptions is still considered a research gap (Ivanov et al. 2014, Snyder et al. 2016). At the interface of disruption risks and sustainable inventory management, lead-time and service level control issues play an important role. These issues have previously been investigated in the SC coordination setting (Chaharsooghi et al 2011, Heydari 2014, Heydari and Asl-Najafi 2016) in order to take into account the uncertainty of the reality with the inclusion in the model of some stochastic parameters (Battini et al, 2017).

3. Case-study description and problem statement

3.1. Case study on Tesla

Tesla Motors was founded in 2003 (EdgarOnline 2016). The company designs, develops, manufactures and sells electric vehicles and energy storage products. These electric cars are designed on the technology of the Lithium-Ion Battery (LIB). Tesla Motors delivers and sells its products through an international network which comprises over 350 suppliers and different facilities all over the world. The core of Tesla’s SC network is ten facilities scattered around the world in which all processes of design, engineering development, production, warehousing, assembling, administration, market forecasting and sales and customer management services are concentrated (Table 1).

<table>
<thead>
<tr>
<th>Facility Location</th>
<th>Size [ft²]</th>
<th>Lease Expiration Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palo Alto, California</td>
<td>350000</td>
<td>January 2020</td>
</tr>
<tr>
<td>Hawthorne, California</td>
<td>132250</td>
<td>December 2022</td>
</tr>
<tr>
<td>Lathrop, California</td>
<td>430770</td>
<td>Owned building</td>
</tr>
</tbody>
</table>
The Gigafactory plays an important role in the future strategy of Tesla. The Gigafactory is a new Tesla factory located in Reno, Nevada. The full site completion is scheduled for 2018. In 2020, the factory should reach full operative capacity (Bloomberg, 2016). When completed, the building will cover an area of 10,000,000 square feet (it will be one of the largest buildings in the world), create jobs for 6,500 new employees and be able to produce 50 [GWh/year] of LIBs, enabling the production of 500,000 vehicles per year (AssoElettrica, 2014). The main purpose of the Gigafactory is to concentrate the production of all the LIBs for both the electric vehicles and the energy storage devices in a single facility to utilize scale effect advantages. According to Musk and the managers of Tesla Motors (WIRED, 2016), the construction of the Gigafactory will lead to a reduction in the LIB costs by 30-50% by 2020. According to Chung et al. (2016), in 2015 the global LIB price was around 220-280 [$/KWh] depending on the market, with an average of 270 [$/KWh]. To define the final selling price, the global cost of the battery should be increased by 30-35% to account for the gross margin and the profits of the organization as suggested in Nelson et al. (2011). With the Gigafactory, the company aims to produce 500,000 cars per year within the 2018-2020, while at the moment the company produces around 50,000 cars per year (EdgarOnline, 2016).
Tesla Motors has started different partnerships with several suppliers to secure a sufficient flow of key inputs necessary to the LIB production (i.e. lithium, cobalt, etc.). Tesla has announced a supplying agreement with the company Pure Energy Minerals in the Claytone Valley in Nevada (Fehrenbacher, 2015). At the same time, the reuse of LIB has gained increasing importance and attention in the last decade. With reuse, the LIB lifetime can be increased with a second or third life-cycle.

3.2. *Verbal problem statement*

Consider a six-echelon CLSC with collection points and a recycling plant based on the real SC structure of the company Tesla Motors. The problem is based on the propositions of Tesla’s managers and the market analysts for the period from the 2018 until 2025 (cf. Section 3.1) focusing on the use of lithium in the LIB production for the Tesla German market and its recycling.

The logical structure of the model and of the material flows is shown in Fig. 1.

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**Fig. 1** Closed-loop supply chain for LIB
The lithium supplier is the company Pure Energy Minerals in Nevada. The site for the LIB production is the new Tesla Gigafactory in Reno, Nevada. The warehouse is the distribution center (DC) located in Tilburg, Netherlands that serves the Tesla European market. On the customer side, the model considers the 14 most populous German cities. In Fig. 2, the SC structure described above is presented as it is built in anyLogistix software.

![Global supply chain structure and the European part](image)

*Fig 2: Global supply chain structure and the European part (a screenshot from anyLogistix software)*

The two collection DCs are the hypothetical locations which were derived using a standard center-of-gravity method. The first is located in Berlin and collects the exhausted LIBs from the
customers Berlin, Dresden, Leipzig, Hannover, Bremen, and Hamburg. It is called “collection point north”. The second is located in Frankfurt am Main and collects the LIB from Dortmund, Essen, Dusseldorf, Cologne, Frankfurt am Main, Nuernberg, Munich, and Stuttgart. It is called “collection point south”. The recycling plant is the company Toxco, which is located in Ohio (Tesla, 2016) because of the centralization strategy of the company. This is one of the most advanced recycling plants in the North America and the world and is characterized by innovative processes that assure high energy and material savings.

The general scope of the problem is to analyze how a disruption at one of the collection DCs in the reverse SC may affect the financial, customer and operational SC performance and which recovery policies should be used to restore SC operation and performance.

4. Simulation model

4.1 Simulation model logic

In Fig. 3, the logic of the developed simulation model is presented.
Customer demand for new LIBs generates orders at the DC. The DC operates subject to s,S inventory control policy and places orders at the Gigafactory according to s,S parameters and expected lead-time at the customers. The used LIBs create two flows towards the collection points North and South. The collection points ship the LIBs to the recycling plant. The Gigafactory can order the lithium for LIB production either from the recycling plant in Ohio or from the lithium supplier in Nevada. The costs of purchasing lithium from the recycling plant is lower than from the lithium supplier. However, the capacity of the recycling plant is limited and subject to the flow of the re-used LIBs from the collection points. In the case of a disruption at one of the collection points, this flow would be reduced and the Gigafactory would increase the order quantity at the lithium supplier subject to higher costs. The detailed inventory and production control policies will be explained in Sect. 4.2.

4.2 Input data and assumptions

4.2.1. DCs, factories, customers, supplier

For the DCs and factories, outbound processing cost has been defined \([$/m^3]\) to consider the costs of ordering, storing, handling and delivering the materials. The model focuses only on the costs related to the material handling, i.e. the warehousing costs as 3% of the inventory value based on Azzi et al, (2014). Outbound processing cost for main DC and Gigafactory is 1,080 \([$/m^3]\). The collection points ship exhausted LIBs that have already performed two or three life-cycles. For this reason, we consider a value of inventory of 30% compared to the new batteries (324 \([$/m^3]\)). The lithium supplier is an external supplier with its own goals, information systems, production, and transportation strategies. This causes an increase in the costs of deliveries and ordering. For this reason, we consider an outbound processing cost of 9% at the inventory value (2000 \([$/m^3]\)). For the recycling plants an outbound processing cost is 600 \([$/m^3]\).
At Gigafactory, fixed costs are considered. The Gigafactory will hire 6,500 employees at full capacity to produce 500,000 vehicles per year (AssoElettrica, 2014). Considering that the model focuses only on the German market with 40,000 cars per year, we take into account a total number of employees equal to 520, which is calculated as $6,500 \times (40,000/500,000)$. Considering an average salary of 1,400 [$/month], the wage costs is defined as 728,000 [$/month].

4.2.2. Products

We consider two different products shipped along the SC: lithium and LIB. Although in the LIB production different lithium carbonates are used, without loss of generality we assume the use of pure lithium. For 1 kg of lithium, we assume a volume of 0.002 [m$^3$] and a cost of 45 [$/Kg]. The lithium price is derived by USGS (2012) and Wang et al. (2014). For the LIB, the values are an average based on the typical battery of 85 [KWh] used in the Tesla Roadster and model S. We consider an actual price of the LIBs of 160 [$/KWh] (WIRED, 2016). One battery has a weight of 450 [Kg] and a volume of 0.37 [m$^3$] (Berdichevsky et al., 2006). Considering an 85 [KWh] battery with a price of 160 [$/KWh] results in a total cost of 13,600 [$]. This cost is increased by 30% to account for organization profits (Gaines et al., 2000; Nelson et al., 2011). The selling price is therefore 18,000 [$/battery]. The final recycling cost of one battery is as 700 [$/battery].

4.2.3. Demand

Since Gigafactory Tesla aims at producing 500,000 [vehicles/year] (AssoElettrica, 2014) and Europe is the second largest market for the electric cars, a future increase in Tesla’s sales due to the Gigafactory is assumed. According to the new report of non-governmental organization Transport & Environment, until 2025 the number of electric cars in Europe will rise to over 500,000 (CNBC, 2016). In only the first half of 2016, more than 91,000 electric cars have been sold in Europe (Clean Technica, 2016). Among European countries, Germany is the second big-
gest market after Norway. Furthermore, the German government invested in incentives to promote the spread of electric cars. The scope is to reach 500,000 electric cars in Germany (Eccheli, 2016). At the moment, the European market impacts 30-40% of Tesla’s global sales (model S + model X), with around 18,000 cars sold per year in Europe (Tesla Motors, 2016). By considering the current Tesla European sales, the incentive factors stated above and by projecting the current Tesla market share in Europe based on increased production in the future, it is realistic to forecast a future demand of 40,000 vehicles per year for the German market as shown in Table 2.

**Table 2: Customer demand**

<table>
<thead>
<tr>
<th>CUSTOMER</th>
<th>POPULATION</th>
<th>MARKET SHARE</th>
<th>ANNUAL DEMAND [pz/year]</th>
<th>WEEKLY DEMAND [pz/week]</th>
<th>( \sigma_d ) [pz/week]</th>
<th>MIN-MAX DEMAND [pz/week]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hamburg</td>
<td>1,798,836</td>
<td>13.43%</td>
<td>5372</td>
<td>112</td>
<td>38</td>
<td>74 - 150</td>
</tr>
<tr>
<td>Munich</td>
<td>1,378,176</td>
<td>10.28%</td>
<td>4112</td>
<td>86</td>
<td>29</td>
<td>57 - 115</td>
</tr>
<tr>
<td>Cologne</td>
<td>1,017,155</td>
<td>7.61%</td>
<td>3044</td>
<td>64</td>
<td>22</td>
<td>42 - 86</td>
</tr>
<tr>
<td>Frankfurt am Main</td>
<td>691,518</td>
<td>5.21%</td>
<td>2084</td>
<td>44</td>
<td>15</td>
<td>29 - 73</td>
</tr>
<tr>
<td>Stuttgart</td>
<td>613,392</td>
<td>4.62%</td>
<td>1848</td>
<td>39</td>
<td>13</td>
<td>26 - 52</td>
</tr>
<tr>
<td>Dusseldorf</td>
<td>592,393</td>
<td>4.44%</td>
<td>1776</td>
<td>37</td>
<td>13</td>
<td>24 - 50</td>
</tr>
<tr>
<td>Dortmund</td>
<td>580,956</td>
<td>4.34%</td>
<td>1736</td>
<td>36</td>
<td>12</td>
<td>24 - 48</td>
</tr>
<tr>
<td>Essen</td>
<td>573,468</td>
<td>4.28%</td>
<td>1712</td>
<td>36</td>
<td>12</td>
<td>24 - 48</td>
</tr>
<tr>
<td>Bremen</td>
<td>548,319</td>
<td>4.12%</td>
<td>1648</td>
<td>35</td>
<td>11</td>
<td>24 - 47</td>
</tr>
<tr>
<td>Leipzig</td>
<td>531,809</td>
<td>3.97%</td>
<td>1588</td>
<td>33</td>
<td>11</td>
<td>22 - 44</td>
</tr>
<tr>
<td>Dresden</td>
<td>529,781</td>
<td>3.95%</td>
<td>1580</td>
<td>33</td>
<td>11</td>
<td>22 - 44</td>
</tr>
<tr>
<td>Hanover</td>
<td>525,875</td>
<td>3.92%</td>
<td>1568</td>
<td>33</td>
<td>11</td>
<td>22 - 44</td>
</tr>
<tr>
<td>Nuernberg</td>
<td>510,602</td>
<td>3.81%</td>
<td>1524</td>
<td>32</td>
<td>10</td>
<td>22 - 42</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>13,394,152</td>
<td>100%</td>
<td>40000</td>
<td>834</td>
<td>----</td>
<td>557-1134</td>
</tr>
</tbody>
</table>

Total demand is distributed among the different customers (i.e. German cities) depending on their population. The population of each city is then divided by this value to find its market
share. The annual demand is multiplied by this market share to determine the mean annual demand for each customer region and the mean weekly demand (the model considers one year constituted of 12 months of four weeks each).

The demand is considered normally distributed in the different periods (i.e. weeks) with a standard deviation \( \sigma \) equal to 1/3 of the mean value. The mean demand is constant throughout the year. The different customers have an expected lead-time of 15 days with an allowed backorder policy (the delayed orders are postponed but not dropped).

Even if the LIBs may be directly re-used after their first life-cycle with a simple operation of inspection and cleaning, we focus only on the recycling of the LIBs. We assume a battery return rate of 75%. The reverse flows subject to shipment frequency of five days for the different customers are shown in Table 3.

Table 3 Reverse flows to collection points North and South

<table>
<thead>
<tr>
<th>Reverse customers</th>
<th>Collection point</th>
<th>MIN–MAX FLOW [pz/shipment]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berlin</td>
<td>North</td>
<td>73-145</td>
</tr>
<tr>
<td>Hamburg</td>
<td>North</td>
<td>37-75</td>
</tr>
<tr>
<td>Bremen</td>
<td>North</td>
<td>12-24</td>
</tr>
<tr>
<td>Leipzig</td>
<td>North</td>
<td>11-22</td>
</tr>
<tr>
<td>Dresden</td>
<td>North</td>
<td>11-22</td>
</tr>
<tr>
<td>Hanover</td>
<td>North</td>
<td>11-22</td>
</tr>
<tr>
<td>Dusseldorf</td>
<td>South</td>
<td>12-25</td>
</tr>
<tr>
<td>Essen</td>
<td>South</td>
<td>12-24</td>
</tr>
<tr>
<td>Frankfurt</td>
<td>South</td>
<td>15-37</td>
</tr>
<tr>
<td>Cologne</td>
<td>South</td>
<td>21-43</td>
</tr>
</tbody>
</table>
4.2.4. Vehicle types and paths

We consider four different types of vehicles for the shipments. For the deliveries from the supplier to Gigafactory and from the end customers to the collection points, trucks’ cargo compartments have a capacity of 15,000 kg and 50 m³. For the deliveries from the main DC to the customers the model uses a eurotruck with capacity of 22,000 kg and 70 m³. For both types of trucks, we assume speed to be normally distributed with mean and σ of respectively 50 and 20 km/h. For transportations from Gigafactory to Main DC and from the collection points to the recycling plant, we assume the use of Boeing 777-200ER aircrafts with a capacity of 50,000 kg and 90 m³. For shipments from the recycling plant to Gigafactory, we assume the use of Boeing 777-200 aircrafts with a capacity of 20,000 kg and 60 m³. The choice was made based on common practice in intercontinental and national American transportation. For the air transportation, we assume a normally distributed speed with mean and σ of respectively 700 and 100 km/h.

For the transportation costs computation, a weight-distance based policy is used. The cost of trucks is defined as 0.00015 [$/Kg*Km] and for the air transportation as 0.00062 [$/Kg*Km] based on the works of Hummels (2007), Lupi (2012) and Battini et al. (2014).

The model considers an LTL transportation policy with a minimum load ratio of 0.9 and an aggregation period of five days. The choice of such a short aggregation period is made to improve the service level (i.e., to increase the ratio of customer on-time orders). In the return routes from

<table>
<thead>
<tr>
<th></th>
<th>South</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dortmund</td>
<td></td>
<td>12-24</td>
</tr>
<tr>
<td>Munich</td>
<td></td>
<td>29-58</td>
</tr>
<tr>
<td>Nuernberg</td>
<td></td>
<td>11-21</td>
</tr>
<tr>
<td>Stuttgart</td>
<td></td>
<td>13-26</td>
</tr>
</tbody>
</table>
the customers to the main DC, a distance-based transportation policy with a cost of 0.95 [$/Km] is used (Analisi dei costi nei trasporti, 2012, p. 13).

4.2.5. Inventory

To define the inventory level at the main DC, we assume a MIN-MAX policy with safety stock. Due to the lack of historical data, we assume that a safety stock SS equals the mean weekly demand (834 batteries). This means that the MIN (s) and MAX (S) inventory levels are as follows:

\[ s = SS + (\sigma_d \times LT) = 834 + (834 \times 1.4) \approx 2000 \text{ [LIB]} \]

\[ S = 2 \times s = 4000 \text{ [LIB]} \]

The model considers an initial stock of 2,834 batteries to cover the minimum level of inventory and the safety stock at the beginning of the simulation run. These values of inventory are then projected backwards along the SC in order to assure the capability of production and the availability of material necessary to satisfy the end customer demand. For the products needed for the production policies, a reorder point-reorder quantity policy \((R, Q)\) is assumed. The inventory policies defined for different SC facilities are summarized in Table 4.

**Table 4: Inventory control policy parameters in the supply chain**

<table>
<thead>
<tr>
<th>FACILITY</th>
<th>PRODUCT</th>
<th>INVENTORY POLICY</th>
<th>R</th>
<th>Q</th>
<th>SS</th>
<th>s</th>
<th>S</th>
<th>INITIAL STOCK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium supplier</td>
<td>lithium</td>
<td>infinite</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>(\infty)</td>
</tr>
<tr>
<td>Gigafactory</td>
<td>lithium</td>
<td>R-Q</td>
<td>130000</td>
<td>50000</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>180000</td>
</tr>
<tr>
<td>Gigafactory</td>
<td>LIB</td>
<td>MIN-MAX</td>
<td>-----</td>
<td>-----</td>
<td>834</td>
<td>3000</td>
<td>3500</td>
<td>3834</td>
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<tr>
<td>Collection Point North</td>
<td>LIB</td>
<td>MIN-MAX</td>
<td>-----</td>
<td>-----</td>
<td>150</td>
<td>300</td>
<td>550</td>
<td></td>
</tr>
<tr>
<td>Collection Point South</td>
<td>LIB</td>
<td>MIN-MAX</td>
<td>-----</td>
<td>-----</td>
<td>150</td>
<td>300</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>Recycling Plant</td>
<td>LIB</td>
<td>R-Q</td>
<td>1200</td>
<td>920</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>800</td>
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<tr>
<td>Recycling Plant</td>
<td>lithium</td>
<td>MIN-MAX</td>
<td>-----</td>
<td>-----</td>
<td>33000</td>
<td>50000</td>
<td>90000</td>
<td>50000</td>
</tr>
</tbody>
</table>
4.2.6. Production

We define two production policies. The first one is related to the Gigafactory and is based on the BOM (bill-of-material) “battery”. The production cost of one battery is $13,600. According to Gaines et al. (2000) and Chung et al. (2016), the materials comprise 75% of the total battery cost. For this reason, we assume that production costs equals 25% of the total cost. Since the cost of LIBs have constantly decreased in the last years due to improvements in the production processes, we assume an ulterior reduction of 25% of the production cost for a LIB. Therefore the cost is defined as 2,500 $/battery.

The second production policy occurs at the recycling plant and is based on the BOM “reverse lithium”. The recycling process uses from 30% to 70% of the energy necessary for the primary production process and recovers from 50% to 95% of the lithium. Furthermore, Toxco is one of the most advanced recycling plants of the world. For these reasons, we assume a lithium recovery rate of 80% and an energy consumption of 40% compared to the battery primary production. The recycling plant spends $1,000 to recycle a single LIB and recover 48 kg of lithium. For the production of a single LIB, a hypothetical negligible time of 5 minutes (0.0035 [days/batteries]) is assumed.

4.3. Performance indicator computation

For SC performance analysis, three groups of KPI have been considered: financial, customer and operational. Financial performance is measured by revenues and profits. For profit computation, the following costs have been considered: lithium purchase costs, transportation costs, fixed warehousing costs, outbound processing costs at the DCs, manufacturing costs and fixed operating costs at Gigafactory, inventory holding costs at the DCs, and the LIB price. Customer performance has been measured using service level KPIs and the number of arrived and in-time
orders. An order is considered as an in-time order if it has been delivered in accordance with the expected lead-time to the customer. Two service levels, i.e., alpha service level and ELT (expected lead time) service level have been computed. Alpha service level depicts the probability that all customer orders arriving within a given time interval will be completely delivered from stock on hand, i.e. without delay. ELT service level depicts the ratio of orders delivered within “Expected lead time” to total number of orders. Note that in alpha service level, no backlog is considered. If an SC can’t fulfil the order, the order is rejected. The ELT service level takes into account backlog and transportation time to the customer. Operational performance has been computed in regard to inventory dynamics, inventory on-stock and backlogs.

4.4. Disruption and recovery scenarios

SC performance impact is analysed when a disruption occurs in the reverse SC at the collection point North. SC performance is analysed without and with recovery policies for disruption impact mitigation. It is assumed that, once the disruption has occurred, the collection point North remains disrupted for all the remaining periods of analysis. The reason for this choice is to analyze the different effects of the recovery policies over a long period of time. For the reactive recovery policy “Transportation Management”, the collection point South receives part of the batteries shipped by the reverse customers north. The aim of this policy is to reduce the amount of batteries disposed to avoid the resulting high financial losses. In this way, increases in the amount of lithium at the recycling plant favor recycling by increasing shipment quantities from the recycling plant. For the reactive recovery policy “Backup Collection Point”, we introduce a back-up DC that can handle the flows that would have been directed to the disrupted collection point North but at higher costs.
5. Experimental analysis and managerial insights

In this Section, the results of several simulations runs in anyLogistix are presented. We first describe the results obtained in the normal state when no disruption occurs. Subsequently, the disrupted scenarios with and without recovery policies are analysed.

5.1 Normal mode performance analysis

5.1.1. Operational performance

In Fig. 4, an overview of shipped and received lithium is presented.

![Lithium Shipped](image)

Fig. 4. Overview of shipped and received lithium

It can be observed in Fig. 4 that the improvement in the recycling processes permits Tesla Motors to achieve an extremely high recovery rate of lithium. This appears clearly from the comparison of the number of items shipped by the recycling plant and the DC. In this scenario, the company can satisfy more than a half of the production requests at the Gigafactory with recovered lithium obtained from the recycling plant. The inventory dynamics at LIB level is shown in Fig. 5.
Fig. 5 depicts the LIB available inventory at the main DC, collection DCs, recycling plant, and Gigafactory. It can be observed from Fig. 5 that both main DC and Gigafactory operate without backlog. The normal operation of both collection DCs in the reverse SC enable regular shipments to the recycling plant. The observed inventory dynamics could also suggest the importance of increasing the LIBs’ recovery rate and the possibility of storing some quantity of batteries as a strategic stock to avoid possible shortages in case of disruptions.

5.1.2. Customer performances

In Table 5, performance on the customer side is summarized.

Table 5 Customer performance in normal-state scenario

<table>
<thead>
<tr>
<th>Customers</th>
<th>Total Orders</th>
<th>Orders Arrived</th>
<th>In-time Orders</th>
<th>SLa</th>
<th>SL_ELT</th>
</tr>
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<tr>
<td>Berlin</td>
<td>52</td>
<td>52</td>
<td>52</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>City</td>
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<td>51</td>
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<td>1</td>
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<td>----</td>
<td>----</td>
<td>----</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Bremen</td>
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<td>51</td>
<td>51</td>
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<td>1</td>
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<td>51</td>
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<td>1</td>
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<td>51</td>
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<td>1</td>
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<td>Dusseldorf</td>
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<td>Essen</td>
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<tr>
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<tr>
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<td>1</td>
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<td>1</td>
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<td>51</td>
<td>51</td>
<td>1</td>
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<tr>
<td>Nuernberg</td>
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<td>1</td>
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<tr>
<td>Stuttgart</td>
<td>52</td>
<td>51</td>
<td>51</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

It can be observed from Table 5 that service level equals 100% and average lead time is between 1 and 4 days.

5.1.3. Financial performance

In normal-state scenario, revenue is $788,573,444 and total profit is $337,349,780.

5.2. Disrupted Scenario

5.2.1. Operational Performance

In Figs 6 and 7, the performance impact in the disruption scenario (i.e., disruption at the collection point North) is depicted.
Fig 6: Lithium available inventory (disrupted scenario)

Fig 7: LIB available inventory (disrupted scenario)

Due to the disruption, the amount of batteries received at the recycling plant is significantly reduced as shown by the reduced number of orders received. This causes a consequent reduction in
the amount of lithium produced as compared to the normal-state scenario. To ensure the production capability, the Gigafactory must compensate for this difference of lithium by acquiring additional materials from the supplier with increasing material purchasing costs. Furthermore, the LIBs shipped by the reverse customers North are redirected to the disposal centre. These batteries are then disposed with extremely high costs and waste of material.

It can be further observed that the level of lithium at the recycling plant starts to drastically drop once the disruption has occurred, which leads to large orders to supplier. Despite the fact that the model assumes that the lithium supplier has an infinite amount of lithium available, it is possible to see how, immediately after the disruption (day 60), the average amount of lithium at the Gigafactory starts to decrease. Furthermore, around day 140, the chart assumes an irregular trend with great variations in value and the average amount of lithium starts to decrease. This may be seen in the several minimum peaks, far below the re-order point, which start to appear on day 220. These sudden variations are likely to make it more difficult for the company to plan the production in the Gigafactory. Furthermore, an eventual disruption at the supplier could lead to the Gigafactory lacking raw material and to a consequent incapability of production.

5.2.2. Customer performances

Despite the disruption and the problems in the inventory control area pointed out in Sect. 5.2.1, the company is still able to maintain the promised service level of 100%. This indicates that the SC design is robust.

5.2.3 Financial Performances

Table 6 presents the financial performance in the SC in disrupted scenario.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Revenue</th>
<th>Profit</th>
</tr>
</thead>
</table>

Table 6. Financial performance in the SC in disrupted scenario
Due to the lack of recycling in the disrupted scenario, there is a decrease of $40,017,143 of total profit compared to the normal-state scenario. In order to prevent this extremely high loss, it is necessary to plan some recovery actions.

5.3. Reactive Recovery Policy - Transportation Management

In this scenario, the Collection Point South receives part of the batteries shipped by the reverse customers north. The aim of this policy is to reduce the number of batteries disposed to avoid the resulting high financial losses. Due to the increased inventory at the Collection Point South, a revision of the inventory control policy at the recycling plant for the LIBs was necessary. Compared to the normal-state scenario, the re-order quantity Q after the disruption has been increased from 920 to 1100 LIB. Increases in the amount of lithium at the recycling plant favor, in this way, recycling by increasing shipment quantities from the recycling plant (Fig. 8).

5.3.1. Operational Performances

![Lithium Inventory](image-url)
It can be observed from Fig. 8 that despite the evolution of the inventory levels is not as good as the one in the normal-state scenario, the level of lithium at both the Gigafactory and recycling plant is much higher compared to the disrupted scenario and there is no trace of the sudden peaks of minimum/maximum observable in Fig 6.

Fig 9: LIB available inventory (recovered scenario-transportation policy)

An increased number of LIBs at the Collection Point South the new transportation policy can consequently be observed in Fig. 9. It is also important to notice how low the number of LIBs at the recycling plant is. This indicates a shortage of batteries, which are immediately used in the production of lithium once they arrive in the plant.

5.3.2. Financial Performances

Table 7 presents the financial performance in the SC in disrupted scenario and the recovery action “New transportation policy”.

Table 7. Financial performance in the SC in disrupted scenario and the recovery action “New transportation policy”
Table 6 depicts clearly how the implementation of a recovery policy permits a substantial increase in system performances and avoids a loss of $13,642,252, as compared to the disrupted scenario. The financial loss of $26,374,891 compared to the normal-state scenario provides clear evidence of the necessity of avoiding the wastes of batteries due to a lack of recycling.

5.4. Proactive Recovery Policy - Backup Collection Point

5.4.1. Operational Performances

![LIBs Inventory](image)

Fig 10: LIB available inventory (recovery scenario - Backup Collection Point)

Thanks to the Backup Collection Point (Fig. 10), the current operational performance is very similar to the one of the normal-state scenario. It is important to focus on the lithium shipped by
the recycling plant. This proves the effectiveness of this recovery policy for favoring the recycling of the batteries and avoiding waste of material.

5.4.2. Financial performance

Table 8 presents the financial performance in the SC in the disrupted scenario and recovery action “Backup collection point”.

Table 8. Financial performance in the SC in the disrupted scenario and the recovery action “Backup collection point”

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Revenue</th>
<th>Profit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disruption scenario</td>
<td>768211947</td>
<td>291053787</td>
</tr>
<tr>
<td>Disruption-free scenario</td>
<td>788573444</td>
<td>337349780</td>
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<td>Disruption scenario and recovery policy 1</td>
<td>772214900</td>
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<tr>
<td>Disruption scenario and recovery policy 2</td>
<td>780114420</td>
<td>289105422</td>
</tr>
</tbody>
</table>

As we might expect, the backup collection point is extremely expensive and has a strong impact on the financial performances of the company in the period of analysis. It may be pointed out that, compared to the disrupted scenario, the total profit is lower and this could lead to the conclusion that this recovery policy is not effective. However, it must also be considered that, while the expense for the realization of the backup collection point occurs only once, the expense for the batteries disposal continues repeatedly over the time. Due to the backup collection point, it is possible to achieve considerable savings because of the increased recycled LIB number and the consequent reduction in inventory costs.

6. Conclusions

In this paper, we studied the impact of disruptions on SC performance in the closed-loop SC with the help of discrete-event simulation for the first time. More specifically, the objective and con-
tribution of this study is to develop an approach to analyse the disruptions in the reverse part of an automotive CLSC for electric cars (e.g., a temporary unavailability of a warehouse for collecting the used LIBs for electric cars) in regard to (i) their impact on overall SC performance as well as to the (ii) proactive and reactive policies with considerations towards inventory control policies and sustainable manufacturing concepts.

CLSC management is vital in the e-mobility era where lithium batteries play an increasing role in e-cars. At the same time, risk management and resilience in SCs become more and more important in research and practice. Combining these two perspectives, this paper contributes to the existing literature by disruption analysis in the CLSC with the use of simulation and application of the anyLogistix simulation tool in the CLSC analysis. On the basis of a hybrid case study–simulation methodology, this research aimed at analyzing six-stage closed-loop SC of Tesla from the positions of resilience and sustainability. Based on the secondary data, an example for the German market has been created and investigated with the help of discrete-event simulation.

More specifically, the results help to show how a disruption in the reverse SC may affect the financial and operational performances of the company. Two recovery policies in regard to an alternative transportation policy and a back-up collection point have been simulated in order to analyze their capability of recovering the SC from disruption and restoring its operation and performance.

It has been observed that disruption in the reverse SC (i.e., at the LIB collection point) significantly reduces SC performance both at operational and financial levels. Two reactive recovery policies have been subsequently considered. The findings suggest that the recovery plan with the new transportation policy appears more efficient for small-scale and short-duration disruptions and for disruptions that do not completely shut down a site. In this way, the flows of disposed
batteries are not too high and the related costs are low. It is also possible to avoid the high expenses for the backup collection point. The backup collection point recovery strategy appears efficient only for long-lasting disruptions that entirely shut down one or more sites (e.g., due to a natural disaster).

As a limitation of this study, we point out that the model only focused on the Tesla German market under some assumptions made on the basis of secondary data sources. However, by also considering other countries and their markets, it is logical to assume increased LIB flows. In this case, it would be possible to build a larger DC that serves as a backup collection point not only for Germany but also for nearby countries (e.g., Germany-Poland-Czech Republic; or Germany-North Italy - Austria) depending on the facility location. Analysis of this hypothesis could be an interesting future research avenue.

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