Simulation of a Sustainable Cement Supply Chain; Proposal Model Review

Tarek Elhasia, Bernd Noche, and Lima Zhao

Abstract—In recent years, sustainable supply chain management (SSCM) has been widely researched in academic domain. However, due to the traditional operational role and the complexity of supply chain management in the cement industry, a relatively small amount of research has been conducted on cement supply chain simulation integrated with sustainability criteria. This paper analyses the cement supply chain operations using the Push-Pull supply chain framework, the Life Cycle Assessment (LCA) methodology; and proposal integration approach, proposes three supply chain scenarios based on Make-To-Stock (MTS), Pack-To-Order (PTO) and Grind-To-Order (GTO) strategies. A Discrete-Event Simulation (DES) model of SSCM is constructed using Arena software to implement the three-target scenarios. We conclude with the simulation results that (GTO) is the optimal supply chain strategy that demonstrates the best economic, ecological and social performance in the cement industry.

Keywords—Cement industry, simulation, supply chain management (SCM), sustainability.

I. INTRODUCTION

SUPPLY Chain Management (SCM) refers to a managerial philosophy which seeks synchronization and convergence of intra-firm and inter-firm operational and strategic capabilities into a unified, compelling marketplace force; as stated in [1]. As an integrative philosophy, SCM focuses on developing innovative solutions to create unique, individualized sources of customer value.

Traditionally, SCM has played an operational role within the cement industry. Management of the cement supply chains will enable manufacturing operations and integrated logistics into seamless pipelines to maintain the continual flow of cement from the raw materials source to the final customers. Furthermore, SCM is defined as “the task of integrating organizational units along a supply chain and coordinating materials, information and financial flows in order to fulfill (ultimate) customer demands with the aim of improving competitiveness of a supply chain as a whole, Supply chain integration is considered as a systematic connection between the internal and external business processes through management operations to control effectively information, material and cash flow”, as stated in [2] and confirmed by [3]-[4].

Cement, as the most important ingredient of concrete and most mortars, is a fundamental building material for society’s infrastructure construction around the world. Cement consumption rate is known as economic growth- and development index of several countries. In reference to United Nations report [5] “Basic construction materials serve an ever-increasing demand for the building sector; this leads to annual growth rates of about 6% for cement and 3.8% for steel. In the same time these industries caused about 6% of global anthropogenic greenhouse gas emissions”. Cement normally consists of finely ground clinker and 5% Gypsum. Clinker is made from a raw material mix mainly consisting of High carbon- limestone and Clay or their natural blend like lime marl and Correction additives. Cement used in construction is characterized as hydraulic or non-hydraulic. As the most common type of hydraulic cement, Normal-Portland cement (Type I) is the most produced cement worldwide; which is taken as a case study in this research.

As cement is usually delivered to local markets, the cement industry spread their production facilities evenly all over the Federal Republic of Germany and locates near the respective limestone deposits. Cement production is either (wet) or (dry), depending on the water content of the material feedstock. Most of cement plants are operated by Dry-processing worldwide.

Reference [6] gives a clear review about the nature of cement production. Fig. 1 described main manufacturing steps and the most important sustainable aspects in cement industry, starting from the quarry works until the cement silos. Traditionally, these manufacturing steps are divided into five main production processes: Quarrying “Quarry works and crushing”, Raw materials grinding, Clinker production, Cement grinding and cement distracting “Storage & Shipping systems”; as described in Fig. 1.

Simulation has been defined as the imitation of the real-world process or system over time. Simulation tools are specifically designed to limit transient effects on measurements, which can be used in estimating a set of efficiency measures in production systems, inventory systems, manufacturing processes, materials handling and logistics operations. In order to recognize and implement strategies for developing and improving supply chain networks, various techniques have been used in the cement industry.
Computer simulation is one of the popular methodologies to model cement supply chain systems. In order to identify, implement and optimize strategies of cement supply chain framework and to demonstrate the value of sustainable supply chain management in the cement industry, a simulation study of cement supply chain system is carried out.

II. RESEARCH BACKGROUND

A. Scope of Research

The main scope of this research to create and simulate a sustainable cement supply chain; as recommended in [4], by moving Push-Pull boundaries along the supply chain to discuss the feasibility of (MTS, GTO and BTO) strategies; as recommended in [3]. Furthermore proposing a chain of Mini–cement grinding plants; as integration approach.

B. Literature Review

Most research topics reflect the major concerns of the cement industry like cement production, material management and sustainability. Reference [3] proposed cement supply chain frameworks from a business management perspective.

Reference [4] continued the strategic perspectives of [3], analyzed the cement industry more in detail and simulated a traditional cement supply chain model by Arena (Version 10) as an advanced step. Concerning sustainability in cement industry, [7] reviewed the design and operation of the cement value chain from sustainable point of view. Again based on Simulation approach [8] investigated SCM strategies to improve the manufacturing efficiency of cement industry in Libya. In the past few years, the focus on critical issues in cement industry such as climate protection, responsible use of fuels and raw materials, emissions monitoring and reduction has resulted in the broader adoption of sustainability principles into SCM practices. Sustainable supply chain management is a vision of research that is gaining more attention in application. The cement industry has been recently developing strategies for implementing sustainable business management along the value chain. The worldwide leading international cement manufacturers [6] have set up a Cement Sustainability Initiative CSI organized by the World Business Council for Sustainable Development (WBCSD-CSI). In Germany, the social partners of the cement industry have formed the Initiative for sustainability in the German cement industry in 2002, which focuses on topics like Climate protection, the use of alternative fuels and raw materials, industrial safety and health of the employees, emission abatement. The 1st Analysis [6] of the sustainable transport
and logistic chains of German cement industry; published a once in 2004.

C. Research Objectives

In general, this research aims to analyze the essential characteristics of sustainable SCM in the cement industry, to model an integrated cement supply chain from the quarry to the end customers, and to optimize the cement SC through combining key success factors in environmental, economic, and social dimensions.

The environmental dimension of sustainability constitutes to improve thermal and electrical energy efficiency, reduce emissions, and prevent environmental pollution along the cement supply chain. From the economic perspective, the sustainable development of cement companies is largely influenced by the continuous profitability of the cement supply chain network. Our proposed sustainable model aims to increase cement production and distribution efficiency, reduce costs and generate revenue, streamline the cement supply chain processes and enhance competitive advantages. The social dimension of sustainable SCM is frequently related with the concept of Corporate Social Responsibility (CSR), which tries to enhance the cement industry by investing in employee safety and health, local impacts on land and communities, as well as infrastructure and utilities development.

III. SUSTAINABLE SUPPLY CHAIN MANAGEMENT IN CEMENT INDUSTRY

A. Cement Push-Pull Supply Chain Strategies

Considering the response manner to demands, three predominant supply chain systems are the push-model, pull-model and push/pull-model. Due to the high economics of scale as well as the high (bag cement) and low (bulk cement) demand uncertainty in the cement industry, the push-pull strategy is adopted to figure the right cement supply chain framework. Push-pull model takes advantage of risk pooling upstream to produce according to a forecast and keep efficiencies high, while preserving responsiveness downstream. Pull-push batches deliveries efficiently, while holds supply provisioning until demand uncertainty has been revealed. In the supply chain framework, four strategies are commonly used to address competitive priorities of response to market demand: Make-to-stock (MTS), Assemble-to-order (ATO), Build-to-order (BTO) and Engineer-to-order (ETO); these strategies and their Advantages and Disadvantages are reviewed in [9]. Concerning cement industry, MTS and ATO are the most accepted supply chain strategies. Traditionally, the cement supply chain applies push-strategy with a MTS mechanism which produces cement based on demand forecast and holds cement in inventory for immediate customer delivery, so as to minimize lead time to customer. ATO requires efficient and low cost production in the cement manufacturing process and flexibility in the assembly stage to satisfy individualized customer demands. In the cement supply chains, two ATO strategies – Grind-To-Order (GTO) and Back-To-Order (PTO); as reviewed more in detail in [3],[4].

Fig. 2 identified the main cement supply chain processes; based on the three-target supply chain strategies, which are taken as simulation scenarios, later on.

Make-To-Stock strategy/Scenario I provide the fastest response time to customer, but the storage costs can be high and product portfolio is usually limited; which is more suitable for bulk cement supply chain. In order to reduce the storage costs and enrich customer product choices, Assemble-to-order is implemented to handle bag and bulk cement order configurations.

Pack-To-Order strategy/Scenario II helps to cope with the high demand uncertainty of bag cement. MTO can be an option for mass-customization of cement supply chain. With increased variations in bag sizes and cement types in the future, the delay in the cement mixing and packaging process is possible. Therefore, the implementation of PTO is reasonable with more flexibility in customer order fulfillment and a trade-off analysis between the storage costs of cement in bulk and bag.

Grind-To-Order strategy/Scenario III sets the push-pull boundary between clinker production and cement grinding process. GTO uses clinker as an intermediate product, grinding cement as a final product according to customer orders. GTO can integrate customer demand in the cement manufacturing process to reduce variability and improve flexibility in order fulfillment. The implementation of both GTO and PTO requires integrated information flow and coordination along the cement supply chain.

![Cement supply chain network and Scenarios](image)

B. Cement Eco-Balance Analysis

As a spreading evaluation method worldwide, Life cycle assessment (LCA) is a technique for assessing the potential environmental impacts associated with a process or activity from “cradle to grave”, which allows a measurement of environmental performances of products, as identified in DIN EN ISO 14040 [10]. Two basic methods: process analysis and input-output analysis have been combined into the LCA.
method, which provides both completeness and accuracy of the life-cycle inventory. This includes life phases along the supply chain - the quarry, clinker manufacture, cement grinding, and product distribution as in Fig. 3.

Eco-Balance summarizes all the environmentally relevant input and output factors throughout the life cycle of cement.

Emission

International Scholarly and Scientific Research & Innovation 7(3) 2013

World Academy of Science, Engineering and Technology


IV. CEMENT SUSTAINABLE SUPPLY CHAIN MANAGEMENT MODELING

In order to optimize the cement sustainable SCM, a simulation approach is adopted in this research to model the cement supply chain framework. In many cases, simulation studies have been used to gain insight into the behavior of real-world systems under different types of control strategies or to determine the accuracy of analytical models. Nowadays, most of the situations in the domain of simulation modeling can be represented by discrete -dynamic-stochastic models.

The discrete-event simulation (DES) contains stochastic components, and the state variables change only at discrete time moments. In order to model cement supply chains by DES, we use Rockwell Arena-V.10 to build the model, conduct experiments and collect system performance data of Cement SCM.

A. Data Assumption

In the proposal SCM model, an integrated- sustainable cement supply chain is designed with a maximal capacity of one million ton clinker annually. Given the normal plant efficiency of ca. 80%, with 800,000 tpa ”ton per annum” actual production capacity. The operation period of the plants is assumed to be 300 days annually, based on 45 days required for Refractory and Routine maintenance works. Further emergency plant-shutdowns are assumed to be 20 days. The proposal model is described in details in Fig. 4 and (Table I).

B. Physical Model

The quarry is the start point of the cement supply chain, which supplies the raw materials such as limestone, clay, etc. for clinker plant I. In the clinker plant I, the raw materials are delivered to the crushers and then taken by the belt conveyors into the Input inventory for clinker production ”Clinker yard”. The mixture of limestone, clay and other additives is ground in the grinding section; and then conveyed into

Fig. 3 Cement Eco-Balance Structure – Input Output Analysis

The evaluation and the comparison of such inventories make it possible to regard the extent of their environmental impact. In the Eco-Balance structure of cement, three issues are discussed in the Life Cycle Assessment LCA: (Emissions reduction, Thermal energy efficiency and Electricity efficiency).

Nowadays, about 60% of all CO₂ emission from cement production originate from the basic calcination process the heating of limestone to form lime. Ca. 30% comes from usage of fuel, and the remaining 10% from electricity usage and transportation. Reducing CO₂ emission from cement production is a key focus of the cement producers and governments. Improvements of Greenhouse gases emission can be made by enhancing technology and design, striving for continuous measurements and full monitoring coverage, building cleaner plants within higher degree of automation, optimizing de-dusting systems and self-cleaning systems, environmental policies and protocols, as well as the optimization of cement distribution network.

Roadmap of (WBCSD-CS1) gives us the future vision of the sustainability of cement industry.

In reference [11] the German cement industry has set itself the target of reducing specific CO₂ emissions from energy consumption by 28% between 1990 and 2008/2012. Thermal energy supplied by fuel is primarily required for the clinker burning process, while electrical energy is mainly consumed in raw material pretreatment, clinker burning, cooling and cement grinding. The process-technology optimization of rotary kiln plants in the past has resulted in a significant reduction in the fuel energy requirement for cement manufacture. Electricity efficiency has been improved by more industrial specifications for product quality and measures of environmental protection over the past decades.

Market and economic forces generally trigger the closure of inefficient facilities as more advanced technologies are commissioned. To become more energy- and Eco-efficient, the use of alternative fuels besides fossil fuels in the clinker burning process is gaining in importance. By-products from domestic, industrial, or agricultural sources can be used as alternative fuel, to replace partially the traditional fossil fuels.

In 2009, [12] found that the alternative fuels accounted more than 58% of the total fuel energy consumption of the German cement industry. Meanwhile, this reduces the associated environmental impacts of finding, producing, transporting and burning these fuels.

C. Integration Approach

Concerning Cement-Supply chains integration, as described in [4], both of the ”vertical- and horizontal” integration in cement industry. Fig. 4 shows the physical layout including the interconnections of the integrated supply chain modules.

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Homogenizing- and Storage silos. Raw-mix feeding into the Preheater is started by withdrawing material from the Homogenizing silos into the proportioning section "clinker production process"; including Preheater with bypass and fans, Rotary kiln, Grate-cooler.

B. Brady, H. Omrani, O. Hamid, "The demand management section organizes the marketing and sales operations of the cement supply chains including the decision making in different types of product sales: bulk clinker exports, bulk cement sales, distributing Bulk cement as company’s product and sales of cement bags on customer’s demand. These decision points are represented in the logical flowchart in Fig. 5.

C. Logical Flowchart

Most bulk clinker is conveyed directly to the indoor cement grinding plant II or distributed to outdoor cement plants III, IV, V by "River transport", a small portion of 10% of bulk clinker is exported through the seaport, based on market demand. In the four cement grinding plants II, III, IV, V, the transported clinker, gypsum and additives are stored in the cement materials (intermediate) yards "RM II, RM III, RM IV & RM V; these storage units are known as inventory points". After the grinding process in the Cement mill, the cement is conveyed to Silos and stored in bulk. Further masonry cement types are produced in the Mixing-silo, on customers’ demands. Backing unit consists of more than a Cement-backer followed by truck-loading facilities in the truck yard via the belt conveyors. The cement in bulk or bag is delivered according the customer orders in 25 ton Bulk-tank-trucks.
The first decision point DP1 occurs at the clinker output, maximally 10% of clinker are exported through the seaport near the clinker plant I; the most portion is transported to the cement grinding plants II, III, IV, V by inland shipping.

Decision points DP2, PD3 and DP4 happen at the cement distribution centers. Normally, about 10% of bulk cement is exported, while 30% are sold in the domestic market. At DP3 about three quarters are transported as company product to the construction sites, as the rest flows to DP4.

The fourth decision concerns two types of the bag cement sales, where the masonry cement has to be produced 60% according to customer orders. The rest bag cement is sold as Portland cement. All percentages at decision points are assumed according to cement market statistics in Germany.

D. Model Structure

Arena cement supply chain model in Fig. 6 is arranged in 6 stages: quarry, clinker input, clinker output, cement raw material (RM), distribution center (DC) inventory, and customer demand management. In order to keep reasonable inventory levels, the proposed cement supply chains applies the well-known (Q, R) inventory control policy. The inventory has an order quantity Q, and reorder point R. The settings of order quantity and reorder point, as well as production schedules can be used to implement different cement supply chain strategies (MTS, PTO & GTO); as in (Fig. 2).

V. Model Simulation

The demand management module generates the cement demand stream based on statistics at the German cement market, handles customer order fulfillment, and triggers replenishment orders from the cement distribution centers.

The cement orders that arrive at demand management are assumed to be in 25 ton each based on the maximal loading capacity of trucks in Germany. The demand stream at the cement plants II, III, IV, and V consists of orders from the demand management. The input data of cement supply chain model consists of three parts: the scheduled order arrival at demand management, the parameters of module entities, and the variable settings based on supply chain scenarios. The order arrival rate is scheduled based on the cement sales statistics in Germany.

The monthly cement sales statistics on the German market in the recent three years – 2007, 2008 and 2009 are summarized and the average percentages of monthly sales to schedule the order arrival of demand management (Table II). The highest monthly cement demand on the German market occurs in July and the lowest in January.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
<th>Type</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total raw materials</td>
<td>ton per ton clinker</td>
<td>1.6</td>
<td>quoted</td>
<td>VDZ</td>
</tr>
<tr>
<td>Clinker consumption</td>
<td>ton per ton cement</td>
<td>1</td>
<td>quoted</td>
<td>VDZ</td>
</tr>
<tr>
<td>Fuel energy consumption</td>
<td>G.joul/ton cement</td>
<td>2.842</td>
<td>calculated</td>
<td>VDZ</td>
</tr>
<tr>
<td>Electrical power consumption</td>
<td>kWh/ton cement</td>
<td>100.167</td>
<td>calculated</td>
<td>VDZ</td>
</tr>
<tr>
<td>CO2 emissions</td>
<td>ton per ton cement</td>
<td>0.587</td>
<td>calculated</td>
<td>VDZ</td>
</tr>
<tr>
<td>Clinker production costs</td>
<td>EUR/ton clinker</td>
<td>37</td>
<td>quoted</td>
<td>Mc Kinsey, VDZ, BDZ</td>
</tr>
<tr>
<td>Transport costs - Inland shipping</td>
<td>EUR/ton clinker per 100 km</td>
<td>3.5</td>
<td>quoted</td>
<td>Mc Kinsey, VDZ, BDZ</td>
</tr>
<tr>
<td>Road transport costs</td>
<td>EUR/ton clinker per 100 km</td>
<td>8.6</td>
<td>quoted</td>
<td>Mc Kinsey, VDZ, BDZ</td>
</tr>
<tr>
<td>CO2 emissions costs</td>
<td>EUR/ton cement</td>
<td>20.53</td>
<td>calculated</td>
<td>Mc Kinsey VDZ, BDZ</td>
</tr>
<tr>
<td>Transport distances - Inland Shipping</td>
<td>km</td>
<td>to Plants (III:200, IV:400 IV:600</td>
<td>assumed</td>
<td>Data Assumption</td>
</tr>
<tr>
<td>Transport speed - Inland Shipping</td>
<td>km/day</td>
<td>575</td>
<td>quoted</td>
<td>Rodrigue J et al. 2009</td>
</tr>
<tr>
<td>Transport distances - 25 ton truck</td>
<td>km</td>
<td>TRIA (150, 80,10)</td>
<td>assumed</td>
<td>Data Assumption</td>
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<tr>
<td>Transport distances - Small trucks</td>
<td>km</td>
<td>UNIF (80,10)</td>
<td>assumed</td>
<td>Data Assumption</td>
</tr>
<tr>
<td>Transport speed - Truck transport</td>
<td>km / day</td>
<td>600</td>
<td>quoted</td>
<td>Pillay S, 2010</td>
</tr>
<tr>
<td>Transport emissions – Inland Shipping</td>
<td>gram/ton·km</td>
<td>31</td>
<td>quoted</td>
<td>VDZ, BDZ</td>
</tr>
<tr>
<td>Transport emissions – Truck transport</td>
<td>gram/ton·km</td>
<td>158</td>
<td>quoted</td>
<td>VDZ, BDZ</td>
</tr>
</tbody>
</table>
Given the production capacity of 800,000 tpa, 25 operation days per month (based on 300 operation days per year) and the customer order quantity of 25 ton each, the arrival rate per hour is calculated and generated at the demand management module.

In the cement sustainable supply chain model, parameters of raw material, fuel and electrical power consumption, CO₂ emission (Table III) during the production processes are quoted from [13], [14], [15], and the fuel and electrical power consumption, CO₂ emission are the average values based on the figures of recent three years in the German cement industry.

Cement Sustainable SCM Network

**Clinker Plant I**
- Quarry
- Clinker RM input
- Clinker output Inventory

**Indoor Cement Grinding Plant II**
- Demand Management
- Cement RM (Clinker) Inventory
- Cement Distribution Centre

**Outdoor Cement Grinding Plant III**
- Cement RM (Clinker) Inventory
- Cement Distribution Centre

**Outdoor Cement Grinding Plant IV**
- Cement RM (Clinker) Inventory
- Cement Distribution Centre

**Outdoor Cement Grinding Plant V**
- Cement RM (Clinker) Inventory
- Cement Distribution Centre

Fig. 6 Arena Cement Sustainable SCM Model

These input parameters are set into the entities of the clinker manufacturing sub model and cement grinding process sub model to simulate the material flow and energy consumption.

**A. Simulation Scenarios**

The what-if-scenarios are designed according to the cement push-pull strategies in (Fig. 2). Three scenarios are separately implemented based on the supply chain strategies of Make-to-stock (MTS), Pack-to-Order (PTO) and Grind-to-order (GTO), which varies in the inventory levels along the cement supply chain. Given the continuous-review inventory policy (Q,R) the three scenarios can be implemented by setting the R and Q for each module and the change of ordering mechanism, as calculated in (Table IV). The reorder points of cement distribution centres are set based on the storage capacity of cement silo. According to the data assumption of the cement supply chain, the silo capacity is 42,000 m³ with a common Portland cement density of 1.51 ton/m³, the safety stock of each scenario can be therefore calculated.

Scenario 1 based on the Make-to-stock (MTS) strategy, the safety stock of the distribution centers at outdoor cement plants III, IV, V should be about 20% of storage capacity, whereas the reorder point of indoor cement distribution center II is set as 10% of silo capacity (Table I), because the distances from clinker plant I to outdoor cement plants can cause extra transport delays. The order quantity of demand management is set to be same as the safety stock of cement DC; the reorder points of cement RM are calculated according to the clinker to cement ratio of 1 and the order quantity of cement DC; the reorder points of clinker input are calculated according to the raw material to clinker ratio of 1.6 and the order quantity of clinker output.

<table>
<thead>
<tr>
<th>Scenario Design – Parameter Settings of Inventory Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inventory points</td>
</tr>
<tr>
<td>------------------</td>
</tr>
<tr>
<td>Clinker inputs</td>
</tr>
<tr>
<td>92800</td>
</tr>
</tbody>
</table>

TABLE IV
Clinker outputs 54000 58000 15000 16600 3150 3500  
Cement RM II 8000 9000 1400 1500 400 450  
Cement DC II 6000 8000 1200 1400 300 400  
Cement RM (III, IV, V) 14000 15000 4000 4500 800 900  
Cement DC (III, IV, V) 12000 14000 3000 4000 600 800  
Cement demand 38500 42000 8600 10200 1900 2100

R: reorders, Q= quantity

Scenario 2 adopts the Pack-to-Order (PTO) strategy with 5% of storage capacity at outdoor cement plants III, IV, V and 2%at indoor cement distribution center II as safety stock. The other parameters are calculated in the same manner as in scenario 1. In this scenario, the flexibility of the cement supply chain increases as the inventory level decreases.

In scenario 3 of the Grind-to-Order (GTO) strategy, the safety stock of the distribution centers at outdoor cement plants III, IV, V should be about 1% of storage capacity, whereas the reorder point of indoor cement distribution center II is set as 0.5% of silo capacity. Other input parameters can be calculated accordingly in the same manner. Scenario 3 enables minimum inventory level along the cement supply chain.

B. Output Analysis

After the simulation runs of the cement sustainable SCM model based on the three proposed scenarios, the key performance indicators (KPI) of output are categorized and analyzed in aspects of Eco-Balance, cost analysis, inventory and service level in order to optimize supply chain model in the cement industry. To evaluate the Eco-Balance performances of the cement supply chain, three parameters - electrical and fuel energy consumption, CO₂ emissions are taken into consideration. The electrical and fuel energy consumption covers mainly the manufacturing processes of clinker and cement, whereas the CO₂ emissions cover the carbon leakage of both production and transportation processes. The economical aspect of the cement supply chain is estimated in cost structure analysis, which covers the production, transport and possible emissions costs. The efficiency of the SCM can be evaluated in both inventory levels along and the customer service level, which is calculated on the basis of delayed orders and total number of customer orders. The simulation results based on three scenarios are summarized in (Table V).

The simulation results of the sustainable cement SCM model based on the three scenarios of Make-to-stock (MTS), Pack-to-Order (PTO) and Grind-to-order (GTO) strategy (Table V) indicate that the ecological performance factors are improved as the inventory levels of the supply chain decrease, which result in enhanced supply chain flexibility and reduced production volume caused by lower safety stocks. In the cost analysis, the highest total costs occur in scenario 2; whereas scenario 1 has the highest production costs.

The reason is that the small transport batches can cause transportation inefficiency (increased number of transports with rarely fully loaded transport units) therefore increased transport costs in scenario 2. The lowest costs are shown in scenario 3 with the minimum inventory levels.

The inventory levels of outdoor cement grinding plants are calculated in average for output analysis. Both scenario 1 and 2 deliver zero order delays; while the third scenario shows a slightly decreased level of service due to the dramatically decreased inventory levels. The simulation output confirms the result of the cement push-pull supply chain analysis.

<table>
<thead>
<tr>
<th>Inventory levels</th>
<th>Index</th>
<th>Parameters</th>
<th>Units</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
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<td>ton</td>
<td>Scenario 1</td>
<td>5388.4</td>
<td>160.7</td>
<td>345.6</td>
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<tr>
<td>Inventory cement RM (indoor-plant)</td>
<td>ton</td>
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<td>372.0</td>
<td>69.4</td>
<td>19.1</td>
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<tr>
<td>Inventory cement DC (Indoor-plant)</td>
<td>ton</td>
<td>Scenario 1</td>
<td>372.0</td>
<td>101.0</td>
<td>42.5</td>
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<tr>
<td>Inventory cement RM (outdoor-plants; avg.)</td>
<td>ton</td>
<td>Scenario 1</td>
<td>889.7</td>
<td>185.9</td>
<td>37.9</td>
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<tr>
<td>Inventory cement DC (outdoor-plants; avg.)</td>
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<td>1278.4</td>
<td>329.2</td>
<td>25.6</td>
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<td>Inventory customer</td>
<td>ton</td>
<td>Scenario 1</td>
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<td>1350.9</td>
<td>276.5</td>
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<tr>
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<td>Scenario 1</td>
<td>0</td>
<td>0</td>
<td>189</td>
<td></td>
</tr>
</tbody>
</table>

κWh= kilowatt hour, nr. = numbers

VI. CONCLUSION

This paper aims to characterize SCM in the cement
industry, model the cement supply chain from the perspective of sustainability, and optimize the cement SC through enhancing key success factors.

The SCM in cement industry can be characterized by the push-pull supply chain framework and life-cycle assessment (LCA) structure.

The importance of sustainable supply chain management (SSCM) lies in integration and achievement of the environmental, economic and social goals of the cement industry.

In order to improve environmental performance such as emissions reduction, life-cycle assessment (LCA) is used to build the cement Eco-Balance structure with the input-output and process analysis. The cement sustainable SCM framework is modeled with Arena according to the discrete event simulation procedures.

The essential success factors of the cement supply chain model are analyzed in the simulation study as the output key performance indicators (KPI) in aspects of Eco-balance e.g. electrical and fuel energy consumption, CO₂ emission; cost analysis of production, transport and emission, inventory as well as customer service levels.

According to the cement push-pull supply chain framework and output analysis, the optimal SCM strategy for cement industry is Grind-to-order.

This research has faced challenges in regards to limitations of data collection and software capacity along the stages of the simulation modeling. Although most of the input parameters are collected and calculated from reliable sources; there are still limitations such as technical data and storage cost. Besides, the cost analysis has covered the production, transport and emission; storage cost was not generated due to lack of data. Incorporating the storage cost would make the simulation results more precise without changing our conclusion of optimal strategy because the inventory levels are decreasing from scenario 1 to 3.

The simulation study has integrated the economic and ecological dimensions into the cement sustainable SCM model in quantitative manners, but the social aspect e.g. investments concerning the CSR in the cement industry has been analyzed but was not able to be calculated because of limited quantitative research in the social aspect of sustainable SCM.

Given the complexity of the cement sustainable SCM model, the limits of entities in Arena training-version 10.0 was exceeded. Therefore, the simulation modeling had to be carried out in sections and summarized to get the holistic view.

In spite of the research limitations, the near reality simulation results are presented in the output analysis. In the future, the social dimension as well as storage costs should be quantified in subsequent researches.