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 frameworks, 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.

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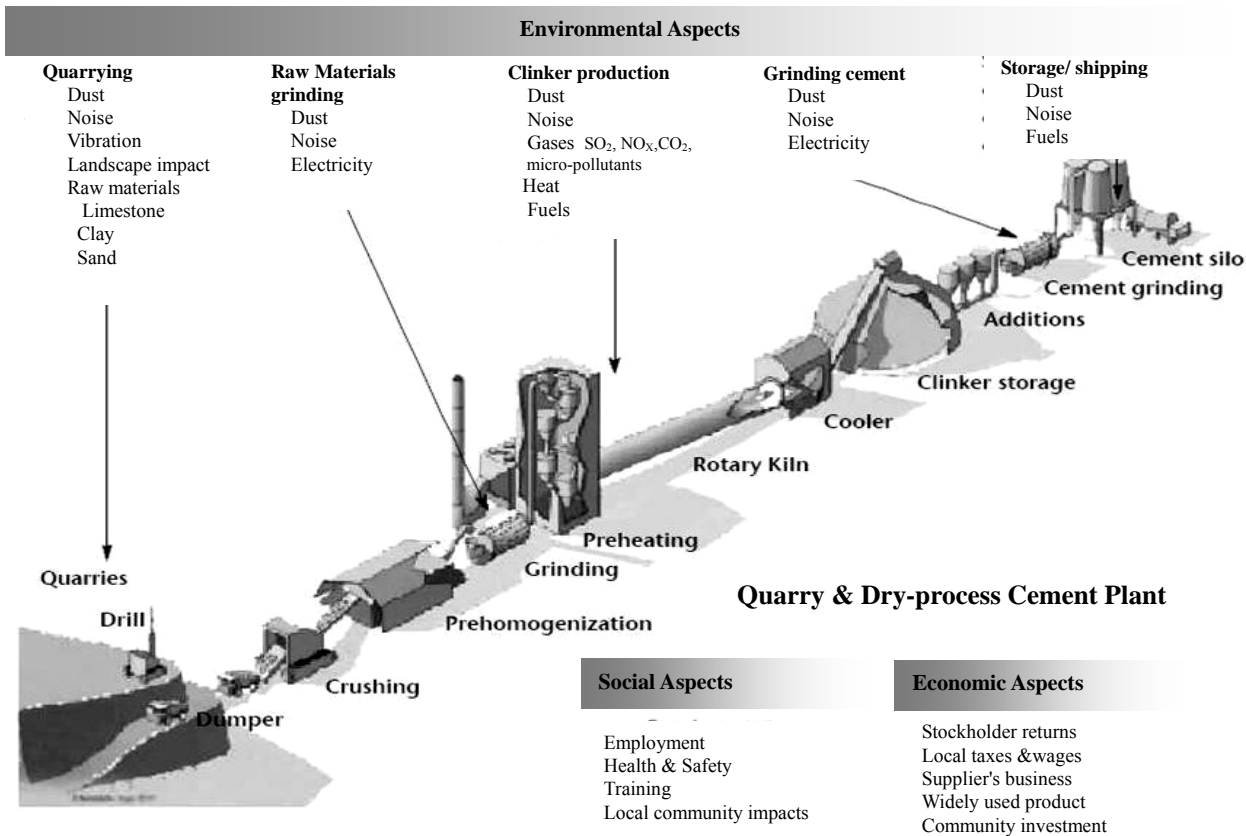
Fig. 1 Layout of cement production line and sustainable aspects

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 enhancing 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 economies 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. PTO 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.
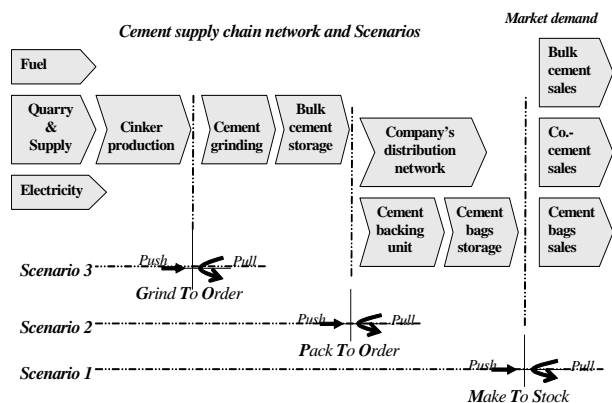

Fig. 2 Cement push-pull supply chain framework; based on (MTS, BTO and GTO) strategies

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.
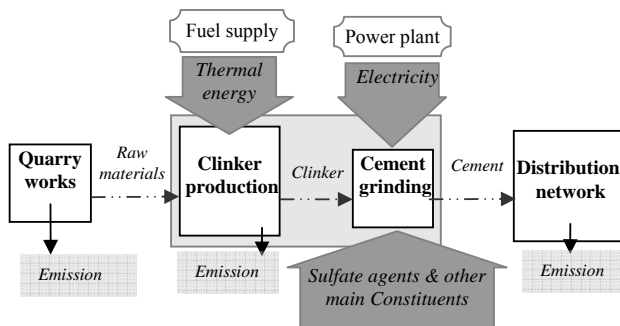

Fig. 3 Cement Eco-Balance Structure – Input Output Analysis

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 CO_2 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 CO_2 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[1] of (WBCSD-CSI) 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 CO_2 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

[1]Cement Roadmap of WBCSD-CSI *targets 2010-2050* (press) URL: http://www.wbcsdcement.org/pdf/technology/WBCSD-IEA_Cement%20Roadmap_centre_spread_actual_size.pdf.

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.

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

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.

Modules	Location	Connected Modules	Capacity (tpa)	Products
Quarry	Close to clinker plant I	Clinker plant I	1.6 million	Limestone, clay, etc.
Clinker plant I	Close to quarry	Indoor terminals, Port terminal	One million	Clinker
Clinker distribution center to Seaport	Clinker storage to Port yard	Seaport, Barge Loading system	200,000	Clinker
Clinker DC to outdoor-cement grinding plants (III,IV,V)	Linked clinker RM storage with plants (III,IV,V)	3 clinker storage facilities of plants (III,IV,V)	200,000 (3)	Clinker
Indoor Portland cement grinding plant (II)	Indoor, close to Clinker Plant I	Indoor terminals, Truck yard	200,000	Masonry-/ Portland bags or bulk Cement
3 Outdoor Portland grinding plant with a Masonry mixing silo	Distances from Clinker to Plants III:200km IV:400km IV:600km	Truck yard Port terminal	200,000 (3)	Masonry-/ Portland Cement bulk / bag
Portland Bulk distribut-ion center	Cement grinding plants	Truck yard Bulk-Loading system	200,000 (4)	Portland bulk cement
Portland bags distribution center	Cement grinding plants	Truck yard Bags-Loading system	100,000 (4)	Portland bags or Masonry bags
Demand Managt.	Market customer sites	Cement Storage	800,000	All of cement sales

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.

Fig. 4 and (Table I) review the proposal model.

Months	Cement Sales 2007 (ton)	Cement Sales 2008 (ton)	Cement Sales 2009 (ton)	Av %	Cement sales (tpm)	Arr per hr.
Jan.	1208617	1308828	698298	4.3	34130	0.6
Feb.	1451120	1722112	1158810	5.8	46160	0.8
Mar.	2132910	1779963	1997258	7.9	63396	1.1
Apr.	2184391	2472403	2218754	9.2	73607	1.2
May	2387877	2347777	2149788	9.2	73675	1.2
Jun.	2509361	2560271	2386513	10	79826	1.3
Jul.	2502612	2633321	2527485	10	82105	1.4
Aug.	2517982	2273125	2199494	9.4	74830	1.2
Sep.	2332999	2622317	2536074	10	80307	1.3
Oct.	2579330	2513438	2395443	10	80176	1.3
Nov.	2241494	2079129	2067536	8.6	68427	1.1
Dec.	1350324	1451206	1252760	5.4	43360	0.7
Sum.	25399017	25763890	23588213		800000	

Av.= average %, Arr hr= arrivals/hour, (tpm)=ton per month
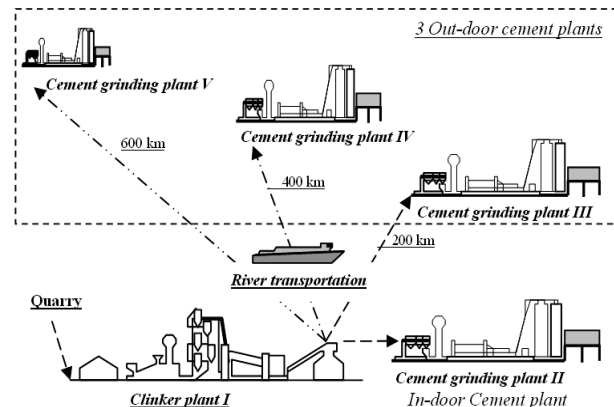

Fig. 4 Physical model (proposed)

C. Logical Flowchart

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.
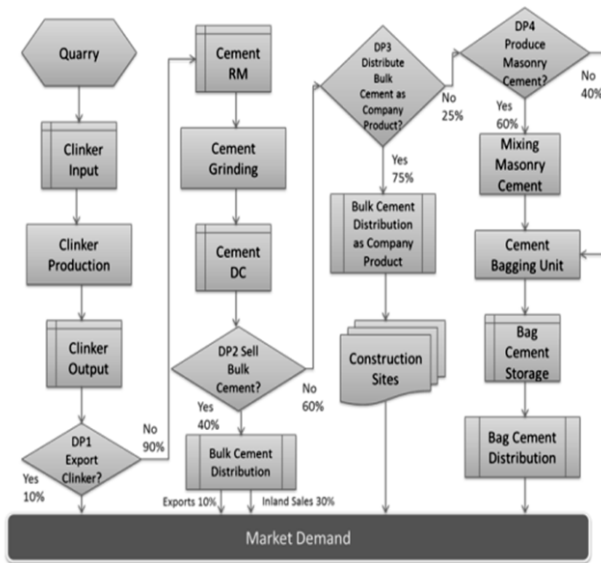
Fig. 5 Logical Flowchart of the Cement Supply Chain

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 III
ENTITY PARAMETERS OF CEMENT SSCM MODEL

Parameter	Unit	Value	Type	Source
Total raw materials	ton per ton clinker	1.6	quoted	VDZ
Clinker consumption	ton per ton cement	1	quoted	VDZ
Fuel energy consumption	G.joul/ton cement	2.842	calculated	VDZ
Electrical power consumption	kWh/ton cement	100.167	calculated	VDZ
CO_2 emissions	ton per ton cement	0.587	calculated	VDZ
Clinker production costs	EUR/ton clinker	37	quoted	Mc Kinsey, VDZ, BDZ
Transport costs -Inland shipping	EUR/ton clinker per 100 km	3.5	quoted	Mc Kinsey, VDZ, BDZ
Road transport costs	EUR/ton clinker per 100 km	8.6	quoted	Mc Kinsey,VDZ, BDZ
CO_2 emissions costs	EUR/ton cement	20.53	calculated	Mc Kinsey VDZ, BDZ
Transport distances - Inland Shipping	km	to Plants (III:200, IV:400 IV:600	assumed	Data Assumption
Transport speed - Inland Shipping	km/day	575	quoted	Rodrigue J.et al. 2009
Transport distances - 25 ton truck	km	TRIA (150, 80,10)	assumed	Data Assumption
Transport distances - Small trucks	km	UNIF (80,10)	assumed	Data Assumption
Transport speed -Truck transport	km / day	600	quoted	Pillay.S, 2010
Transport emissions – Inland Shipping	gram/ton· km	31	quoted	VDZ, BDZ
Transport emissions – Truck transport	gram/ton·km	158	quoted	VDZ, BDZ

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, CO_2 emission (Table III) during the production processes are quoted from [13], [14], [15], and the fuel and electrical power consumption, CO_2 emission are the average values based on the figures of recent three years in the German cement industry.
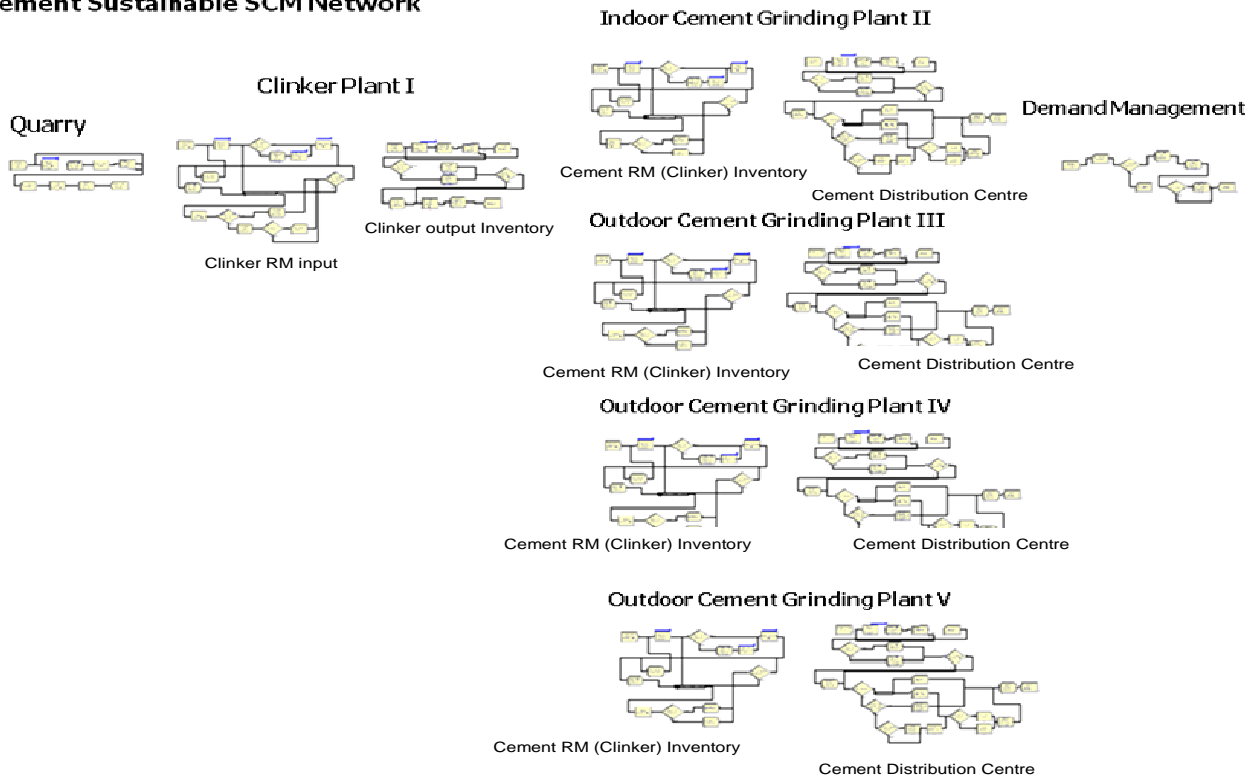

Fig. 6 Arena Cement Sustainable SCM Model

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 of 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 IV
SCENARIO DESIGN – PARAMETER SETTINGS OF INVENTORY LEVEL

Inventory points	Scenario 1		Scenario 2		Scenario 3	
	R	Q	R	Q	R	Q
Clinker inputs	92800	102000	26560	29800	5600	6300

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 (3)	15000 (3)	4000 (3)	4500 (3)	800 (3)	900 (3)
Cement DC (III, IV, V)	12000 (3)	14000 (3)	3000 (3)	4000 (3)	600 (3)	800 (3)
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, CO_2 emissions are taken into consideration. The electrical and fuel energy consumption covers mainly the manufacturing processes of clinker and cement, whereas the CO_2 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 V
OUTPUT DATA - KEY PERFORMANCE INDICATORS

Index	Parameters	Units	Scenario 1	Scenario 2	Scenario 3
Eco-balance	Electrical consumption	kWh	78550961	78488858	65709552
	Fuel consumption	Giga joule	2228696	2226934	1864352
	Emissions	ton	474608	474163	406976
Cost analysis	Production costs	EUR	29015400	28992460	24272000
	Transporta-tion costs	EUR	10289700	10634403	8640426
	Emissions costs	EUR	16214594	16175587	13888956
Σ	Total Costs	EUR	55519694	55802450	46801382
Inventory levels	Inventory clinker input	ton	5388.4	1635.7	345.6
	Inventory clinker output	ton	948.6	537.8	237.4
	Inventory cement RM (indoor-plant)	ton	372.00	69.4	19.1
	Inventory cement DC (Indoor-plant)	ton	372.0	101.0	42.5
Inventory levels	Inventory cement RM (outdoor-plants; avg.)	ton	889.7	185.9	37.9
	Inventory cement DC (outdoor-plants; avg.)	ton	1278.4	329.2	25.6
	Inventory customer	ton	5939.9	1350.9	276.5
Customer service	Delayed orders	nr.	0	0	189
	Order fill rates	%	100	100	99.4

kWh= 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, CO_2 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 emissions; 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.

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