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Application of a system dynamics approach for assessment and mitigation of CO_2 emissions from the cement industry

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Abstract

A system dynamics model based on the dynamic interactions among a number of system components is developed to estimate CO_2 emissions from the cement industry in India. The CO_2 emissions are projected to reach 396.89 million tonnes by the year 2020 if the existing cement making technological options are followed. Policy options of population growth stabilisation, energy conservation and structural management in cement manufacturing processes are incorporated for developing the CO_2 mitigation scenarios. A 42% reduction in the CO_2 emissions can be achieved in the year 2020 based on an integrated mitigation scenario. Indirect CO_2 emissions from the transport of raw materials to the cement plants and finished product to market are also estimated.

Keywords: Cement industry; CO2 emissions; Greenhouse gases; Mitigation options; System dynamics

1. Introduction

Energy use in the industrial sector is responsible for approximately one third of the global carbon dioxide (CO_2) emissions. In India, six industries have been identified as energy-intensive, viz: aluminium, cement, fertilizer, iron and steel, glass, and paper (Schumacher and Sathaye, 1999). The cement sector holds a considerable share within these energy-intensive industries. The CO_2 emissions from cement plants are next only to the coal based thermal power plants. On the global scale the cement industry is responsible for 20% of the man-made CO_2 emissions. This contributes to around 10% of the man-made global warming potential.

In cement making, nearly half of the carbon dioxide emissions result from energy use and the other half from the decomposition of calcium carbonate during clinker production (Hendriks et al., 1999). Moreover, the transport of raw materials and finished products indirectly contributes to the share of CO_2 emission from the cement industry.

At present, the Indian cement industry produces 13 different types of cement; out of which Ordinary Portland Cement (OPC), Portland Pozzolana Cement (PPC) and Portland Slag Cement (PSC) together constitute 99%. Two cement varieties are in use, white and grey. OPC consists of 95% clinker and 5% gypsum. PPC consists of 65% clinker, 5% gypsum and 30% pozzolana. Pozzolana materials include volcanic ash, power-station fly ash, burnt clays, ash from burnt plant material and silicious earths. Pozzolana has siliceous (SiO_2) and aluminous (Al_2O_3) materials that do not possess cementing properties but develop these properties in the presence of water. It has a lower heat of hydration, which helps in preventing cracks where large volumes are being cast. PSC consists of 30% clinker, 5% gypsum and 65% slag. It has a heat of hydration even lower than that of PPC and is generally used in the construction of dams and similar massive structures (Worrell et al., 1995; Karwa et al., 1998).

Limestone is a major raw material used in the production of cement. It is burnt to make clinker and is blended with additives. The finished product is then finely grounded to produce different types of cement (World Energy Council, 1995; Schumacher and Sathaye, 1999). Additives used are mainly fly ash from coal-fired thermal power plants, slag from blast furnaces in the iron and steel industry, pozzolana and natural zeolites. Natural zeolite contains large quantities of reactive SiO_2 and Al_2O_3. Zeolite substitution can improve the strength of concrete by the pozzolanic reaction with $Ca(OH)_2$. This is a reaction in the presence of lime (calcium oxide, CaO) and water to produce reaction products that are cementitious in nature.

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In the cement production process around 0.97 tonne of CO_2 is produced for each tonne of clinker produced. Its distribution is mainly from calcination (0.54 tonne), use of coal and fossil fuels (0.34 tonne) and electricity generation (0.09 tonne) (Marchal, 2001). On an average, around 900 kg of clinker is used in each 1000 kg of cement produced. Thus each tonne of cement is associated with 0.873 tonne of CO_2 emissions (CEMBUREAU, 1996, 1998, 1999; International Energy Agency, 1999; McCaffrey, 2001).

While working out the need for cement production in the coming years, various policy options should be explored keeping in view their environmental aspects. Implications of the policy options and the associated dynamics of CO_2 emissions from the cement industry can be analysed using a System Dynamics (SD) approach. In this dynamic simulation approach information governing the interactions in a system is fed via interactive feedback loops.

In management and social systems, policy-makers and researchers have extensively used SD methodology and conducted policy experiments (Mohapatra et al., 1994). The SD approach has also been applied to a number of studies related to the environment; environmental impact assessment analysis (Vizayakumar and Mohapatra, 1991, 1993), solid waste management (Mashayekhi, 1993; Karavezyris et al., 2002), analysis of greenhouse gas emissions and global warming (Naill et al., 1992; Vrat et al., 1993), investigations of methane emissions from rice cultivation in the Indian context (Anand et al., 2005), water resource planning (Ford, 1996), environmental planning and management (Guo et al., 2001; Guneralp and Barlas, 2003), environmental sustainability (Saysel et al., 2002), ecological modeling (Wu et al., 1993) and many more situations. Though the SD model deals with a system in an integrated sense, the system is decomposed by dividing it into a number of interacting subsystems. The individual subsystems can then be analysed and integrated keeping the mutual interactions among the subsystems.

In this paper we have adopted the System Dynamics methodology for assessment and mitigation of CO_2 emissions from the cement industry in India. The projections of cement production are considered to be mainly influenced by the population growth, the gross domestic product (GDP) increment rate and technologies employed in the cement industry. A software package 'Powersim', which is available for system dynamics analysis has been used in developing a model for the cement sector. The proposed model is a combination of spreadsheet (excel) and system dynamics modeling framework. By interfacing the two the capabilities of both are mutually reinforced, as there is dynamic exchange of data during the course of simulation. Use of a spreadsheet gives the flexibility of manipulating some of the data before it is fed into the system dynamics model, thus enhancing the scope of policy experimentation.

2. System dynamics model for cement sector

In a system dynamics model, the simulations are essentially time-step simulations. The model takes a number of simulation steps along the time axis (Anand et al., 2005). The dynamics of the system are represented by $dN(t)/dt = kN(t)$, which has a solution $N(t) = N_0 \exp t(kt)$. Here, N_0 is the initial value of the system variable, k is a rate constant (which affects the state of the system) and t is the simulation time. For the simulations to start for the first time, initial values of the system variables are needed.

2.1. Causal loop diagram

The SD model for the present studies was developed for scenario building, conducting policy experiments and making projections for CO_2 emissions. A causal loop diagram, shown in Fig. 1, was developed by incorporating the various features associated with the cement sector. A flow diagram was then created from the causal loop diagram and dynamo equations for each element in the diagram were added in the model. The model so evolved was run for a period of 20 years starting from the baseline year 2000.

The mutual interactions associated with cement production and the related CO_2 emissions are qualitatively expressed in the causal loop diagram. Dynamics of the model are determined by the feedback loops of the causal loop diagram. Each arrow of the causal loop diagram indicates the influence of one element on the other. The influence is considered positive (+) if an increase in one element causes an increase in another, or negative (−) in the opposite case. The causal loop diagram is self-explanatory.

2.2. Flow diagram

A flow diagram is useful for showing the physical and information flows in the SD model. Fig. 2a–e show the details of the flow diagram developed for analysing the cement sector. Intricacies of the mutually interacting processes are delineated in the flow diagram.

The level variables are shown as rectangular boxes which represent accumulated flows to that level. A double arrow represents the physical flows, and the flow is controlled by a flow rate. A single line is for showing information flow. Source and sink of the structure are represented by a cloud. The cloud symbol indicates infinity and marks the boundary of the model.

Once the simulation is over, at the end of each step, system variables are brought up to date for representing the results from the previous simulation step. The rate variables are represented by valves. The information from the level variables to the rate variables is transformed by a third variable called the auxiliary variable, represented by circles. The diamonds represent constants, which do not vary over the run period of simulation. A constant is defined by an initial value throughout the simulation. To avoid messing up and criss-crossing in the diagram the variables repeated in the diagram are represented in the form of snapshot variables (frame-like structures).

Five subsystems corresponding to different scenarios are built and discussed in the following sections:

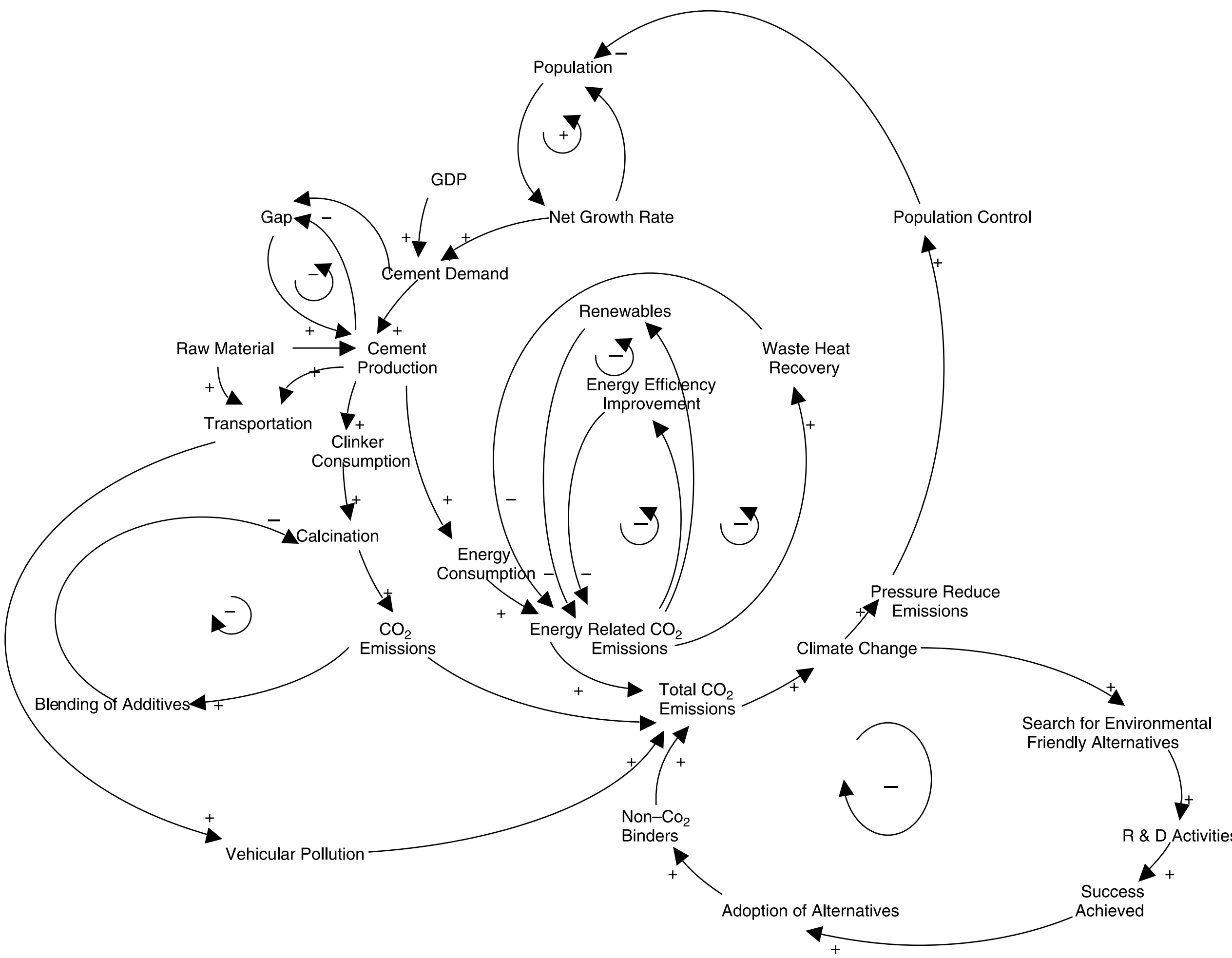

Fig. 1. Causal—loop diagram of the system dynamics model for cement sector.

2.2.1. demand and production

Cement demand and production are taken as level variables. The cement demand represented in Fig. 2(a) would increase with the growth of population and the gross domestic product (GDP). Production should follow the demand and the CO_2 emissions from the plants would likewise increase with more production. This requires information about population, and the population is then considered as a level variable. Its variation obviously depends on the rate of population growth. Percent share of different varieties of cement are worked out and accordingly the clinker consumed in cement production is estimated. Since changes in population growth rate, cement production rate, and percent share of blended cement affect the rate of CO_2 emissions from the cement industry, the impact of these changes is tested using an additional auxiliary named 'switch'. The user can adjust its value to select one of the possible options.

The dynamo equations used to account for the baseline scenario (BS), scenarios 1 and 2 (S1 and S2) in this subsystem are

$$\text{Population} = \text{Population} + dt \times \text{Population\_growth\_rate} \quad (1)$$

where

Population_growth_rate = Population × Conditional_population_growth_rate_multiplier

Conditional_population_growth_rate_multiplier = IF(Switch_A = 1, Population_growth_multiplier_BS, IF(Switcha _A = 2, Popultion_growth_multiplier_S1, Population_growth_multiplier_S2))

Population_growth_multiplier_BS = 0.016 + STEP(−.0003,2001) + STEP(−.0007, +2006) + STEP(−.0006, +2011)

Population_growth_multiplier_S1 = GRAPH(TIME, 2000,1,[0.0162,0.0157, 0.0157,0.0148,0.0139, 0.013,0.0121,0.0112, 0.0103,0.0094,0.0085, 0.0076,0.0067,0.0058, 0.0049,0.004,0.0031, 0.0022,0.0013,0, 0"Min:0;Max:0.02"])

Population_growth_multiplier_S2 = GRAPH(TIME, 2000,1,[0.0162,0.0157, 0.0157,0.0138,0.0119, 0.01,0.0081,0.0062, 0.0043,0.0024,0.0005, 0,0,0,0,0,0,0,0, 0"Min:0;Max:0.02"])

For cement demand and production the dynamo equations used in the model are as follows:

$$\text{Cement\_demand} = \text{Cement\_demand} + dt \times \text{Cement\_demand\_rate} \quad (2)$$

where

Cement_demand_rate = Growth_rate_cement_demand × Cement_demand

Now,

Growth_rate_cement_demand = GDP_increament_rate + Conditional_population_growth rate_multiplier

and, therefore, cement demand can be expressed as

$$\text{Cement\_demand} = \text{Cement\_demand} + dt \times \{(\text{GDP\_increament\_rate} + \text{Conditional\_population\_growth\_rate\_multiplier}) \times (\text{Cement\_demand\_rate})\} \quad (3)$$

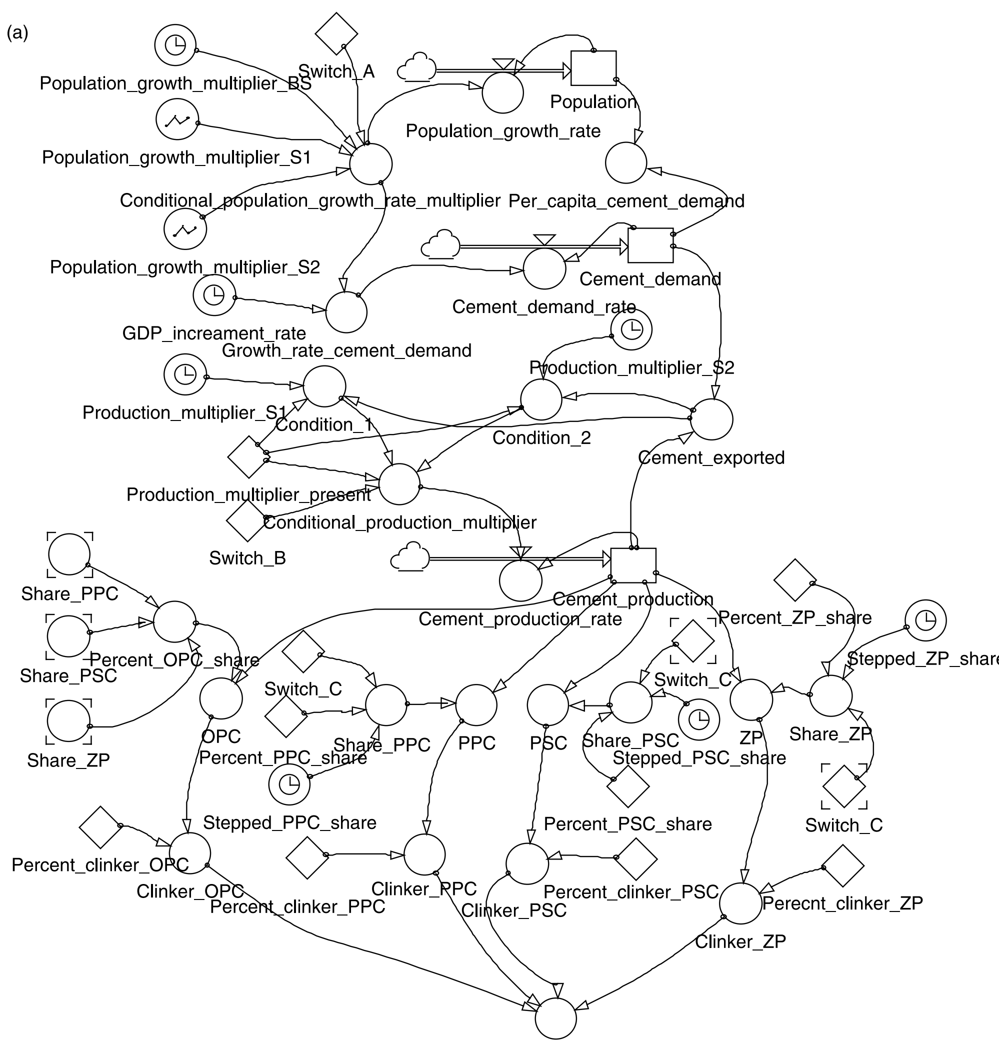

Fig. 2. Flow diagrams of the system dynamics model for cement sector. Subsystem diagrams are labeled as Figs. a–e. Fig. 2 (a) Subsystem depicting the interactions among population, cement demand, cement production and total clinker used. (b) Subsystem for evaluating the electric and thermal energy consumption and total CO_2 emissions. (c) Subsystem for incorporating the coal consumption, fly ash production, pig iron production and slag availability. (d) Subsystem for estimating CO_2 emissions from transport of raw materials (limestone and coal) from their mines to the cement plants. (e) Subsystem for estimating CO_2 emissions due to the transport of cement to market.

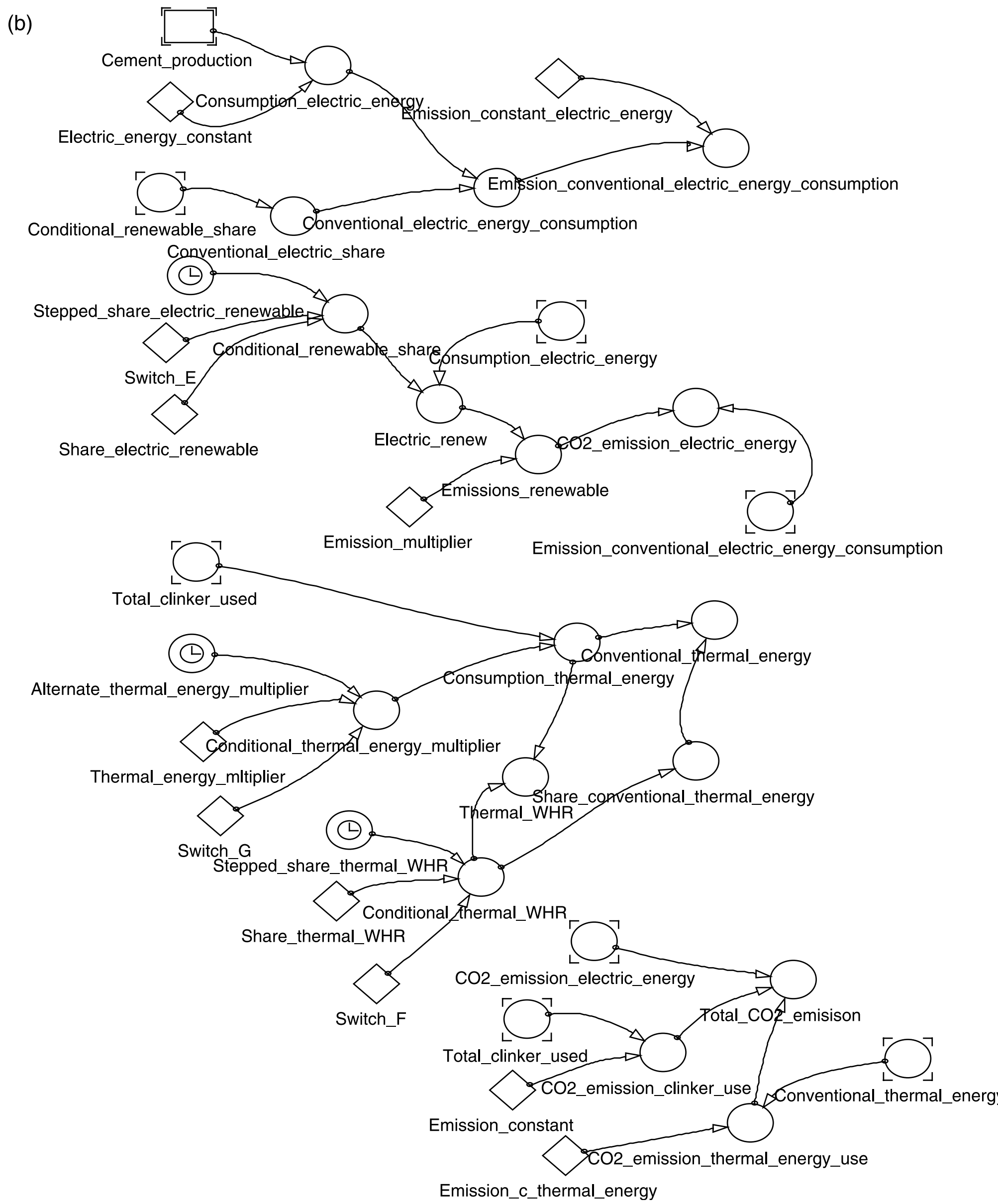

Fig. 2 (*continued*)

$$\text{Cement\_production} = \text{Cement\_production} + dt \times \text{Cement\_production\_rate} \quad (4)$$

$$\text{Cement\_exported} = \text{Cemnent\_production} - \text{Cement\_demand} \quad (5)$$

where,

Cement_production_rate = Cement_production × Conditional_production_multiplier

Conditional_production_multiplier = IF(Switch_B = 1, Production_multiplier_present, IF(Switch_B = 2, Condition_1, Condition_2))

Condition_1 = IF(Cement_exported > 0, Production_multiplier_S1, Production_multiplier_present)

Condition_2 = IF(Cement_exported > 0, Production_multiplier_S2, Production_multiplier_present

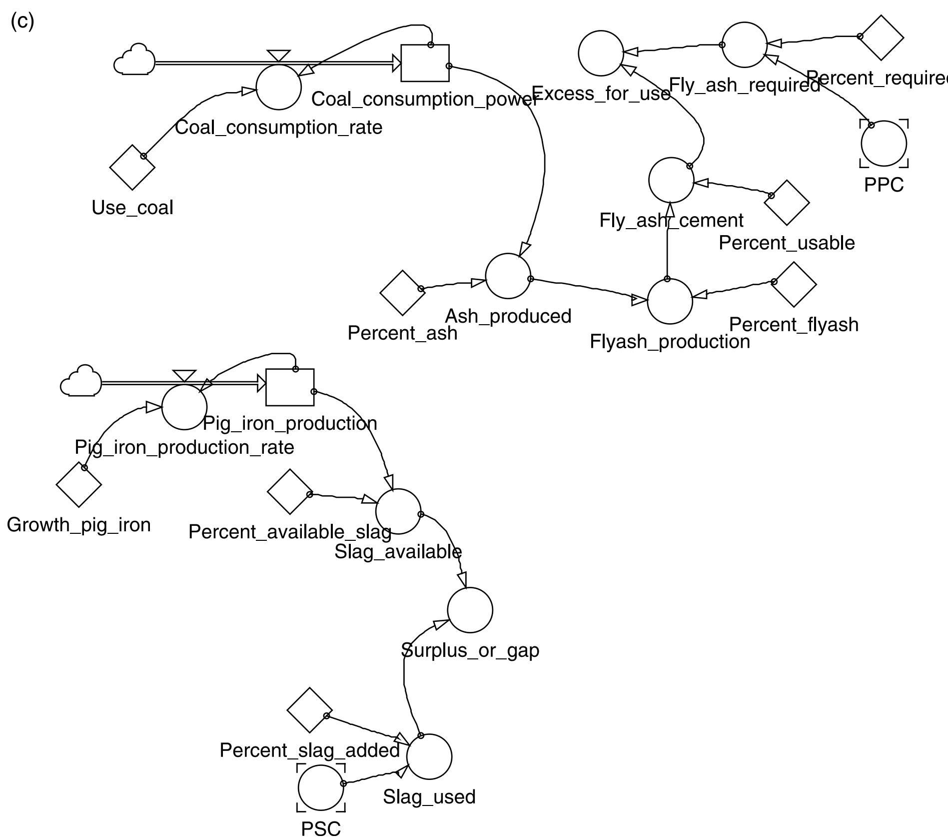

Fig. 2 (*continued*)

where the production_multiplier_present is for the base-line scenario.

Similarly, the dynamo equations were written for energy consumption, availability of slag and fly ash, CO_2 emissions from cement plants and CO_2 emissions arising from transport requirements.

2.2.2. Energy consumption

Electric energy consumption for the cement industry is estimated by considering the electric energy consumed per tonne of cement produced. Its flow diagram is shown in Fig. 2 (b). For the various policy options it is bifurcated into the conventional electric energy and electric energy from renewables. The share of these is varied by a switch function for alternate scenarios. Similarly, the thermal energy consumption is estimated by taking into account the thermal energy consumed per tonne of clinker used. Scenarios considering improved thermal energy efficiency and waste heat recovery are also evaluated under this head.

2.2.3. Avalability of slag and fly ash

The flow diagram shown in Fig. 2 (c) is used to estimate the availability of the blending materials, i.e. slag, fly ash and zeolite. Coal consumption for power generation, taken as a level variable, is calculated and projected for a span of 20 years. For estimating the availability of fly ash it is assumed that on an average the Indian coal has 33% ash content (Mehra and Damodaran, 1993; Choudhary and Bhakatvatsalam, 1997; www.cea-in/opt7-vidyut-chap4.html). Out of this 80% comes out as fly ash during coal combustion in thermal power plants. Approximately, 50% of the wet fly ash disposed in the ash ponds is suited for cement making (Worrell et al., 1995) and the dried fly ash can be lifted from the ash ponds.

Slag is produced in the blast furnace of pig iron plants. In this process 0.7 tonne of slag is generated per tonne of pig iron produced (Worrell et al., 1995).

2.2.4. CO_2 emissions from cement plants

Total CO_2 emissions from cement plants are estimated as the sum total of CO_2 emissions from the consumption of clinker in the process of thermal energy production and generation of electric energy required for the plants. Policy options are implemented while working out the scenarios for the mitigation of total CO_2 emissions over a period of time.

$$\text{Total } CO_2\text{emissions} = CO_2\text{\_emission\_clinker\_use} + CO_2\text{\_emission\_electric\_energy use} + CO_2\text{\_emission\_thermal\_energy\_use} \quad (6)$$

In the mixed mode of production the total clinker used is taken in additive mode

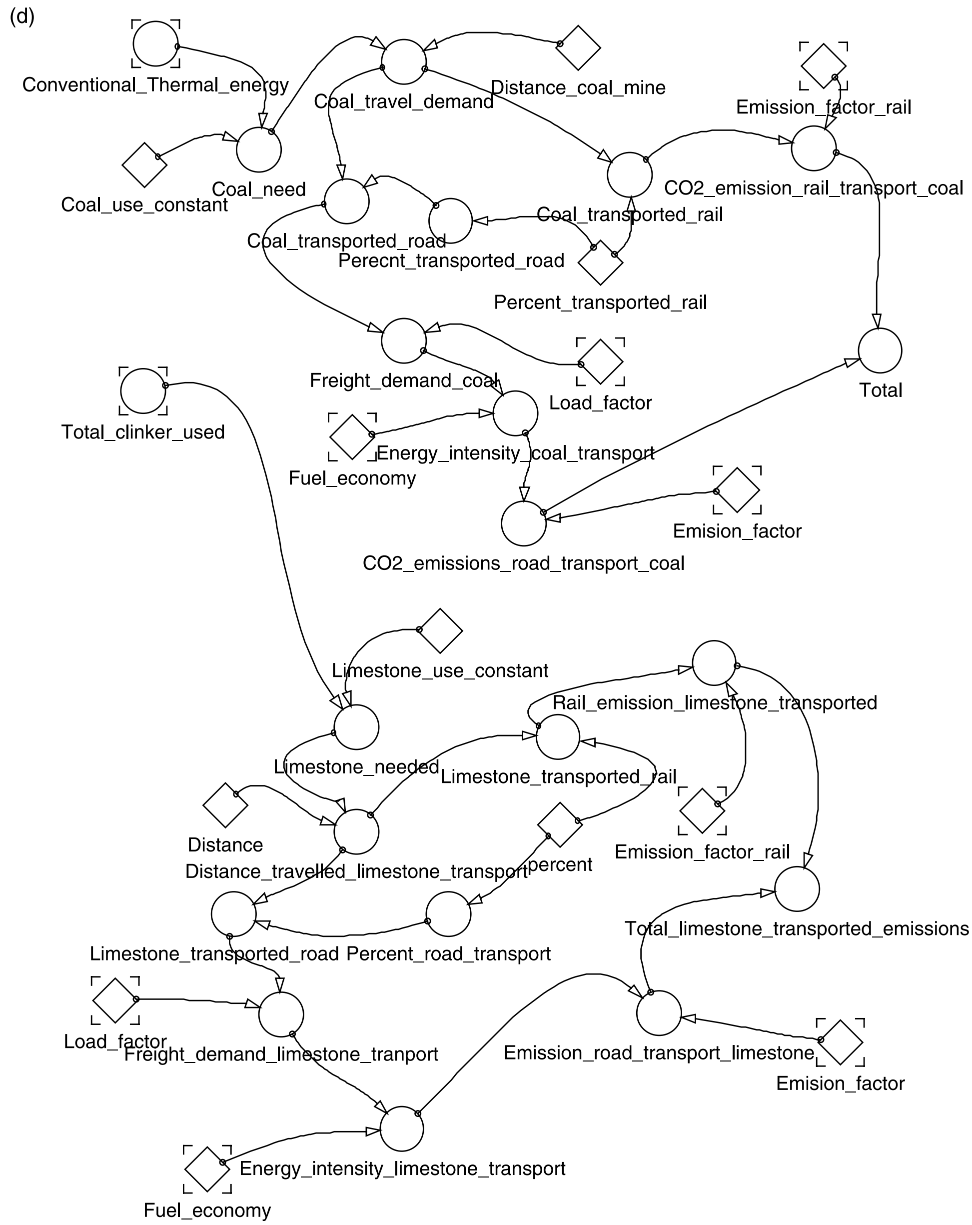

Fig. 2 (*continued*)

$$\text{Total\_clinker\_used} = \text{Clinker\_OPC} + \text{Clinker\_PPC} + \text{Clinker\_PSC} + \text{Clinker\_ZP} \tag{7}$$

where

$$\begin{aligned}
\text{Clinker_OPC} &= \text{Cement_production} \times \text{Percent_OPC_share} \\
\text{Clinker_PPC} &= \text{Cement_production} \times \text{Share_PPC} \\
\text{Clinker_PSC} &= \text{Cement_production} \times \text{Share_PSC} \\
\text{Clinker_ZP} &= \text{Cement_production} \times \text{Share_ZP}.
\end{aligned}$$

2.2.5. CO_2 emissions arising from transport requirements

Cement production requires transportation of raw materials (limestone and coal) to the cement plants. The finished product, cement, is eventually transported to the user market. Transportation is associated with vehicular emissions, which adds to the CO_2 emissions.

Fig. 2 and e represent the respective flow diagrams associated with the CO_2 emissions from the transport of raw materials, limestone and coal to the cement industry and that of cement to the market. The quantity of coal needed for the cement industry is calculated on the basis of thermal energy consumed per tonne of clinker used. Similarly, the calculation is made for limestone needed for clinker production. The respective shares of the rail and road transportation are taken as 55 and 45%. For the rail transported raw materials, the CO_2 emissions are calculated using the emission factor given by

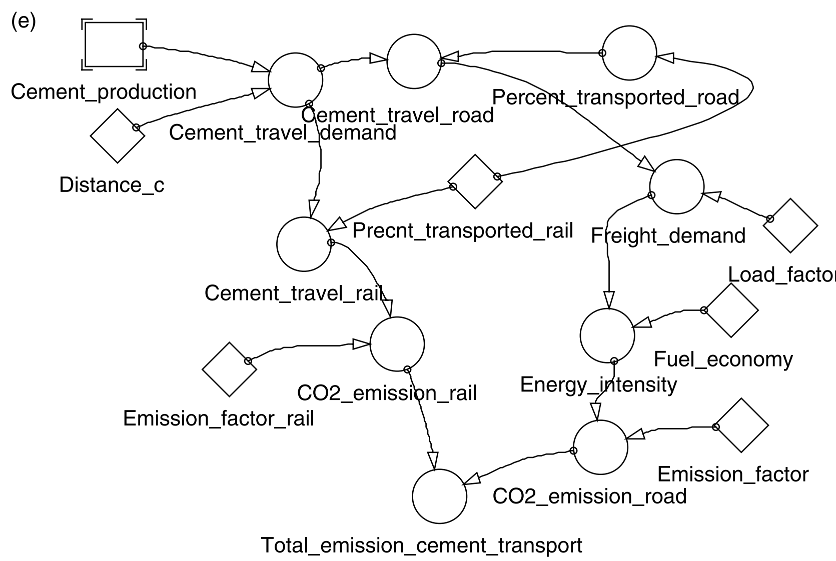

Fig. 2 (*continued*)

IPCC. In the case of the road transport, the energy intensity is calculated from the load factor and the fuel economy. The CO_2 emissions from transportation of raw material and the finished product, cement, are then obtained using the emission factors 0.03 kg CO_2 per tonne kilometer for rail transport and 2.74 kg CO_2 per liter of diesel for road transport. Fuel economy is 3 km per liter and the load factor is 5 tonne kilometer per vehicle kilometer for road transport. This gives 0.183 kg CO_2 per tonne kilometer emission if the road freight is used (GHG Protocol -Mobile Guide, 2001).

3. Scenario generation

Three scenarios are generated under the broad categories of baseline scenario (BS) and modified scenarios 1 and 2 (S1 and S2). Policy options based on structural management and energy efficiency management are implemented in all three scenarios. The model is run for a span of 20 years starting from the baseline year 2000. Data for the population of India and its growth rate are taken from the official figures (GOI, 1997, 2001, 2002).

3.1. Baseline scenario

This scenario is generated for the existing growth rate of the population in the baseline year 2000 without any policy interventions. The energy consumed, the amount of clinker required and the quantity of CO_2 emitted in the process of cement production are calculated at yearly intervals. In the year 2000, India's population was 1014 million and had a growth rate of 1.62%. For analysing various alternatives, a STEP function is utilized. Using the population growth rates given in the Ninth Five Year Plan of India the step sizes are taken as 1.57% from 2001 to 2006, 1.50% from 2006 to 2011 and 1.44% beyond 2011 till 2018. Similarly, the growth rate of the gross domestic product (GDP) is taken as 6% and is stepped up to 8% (GOI, 1997, 2001–2002). As mentioned earlier, the population growth and GDP would have additive effects on the cement demand.

Cement production in India for the year 2000 was 100.4 million tonnes and from the historical trend this seems to increase at a rate of 8.28%. Of the total cement produced, the share of OPC is 67.19%, PPC is 22% and PSC is 11%. Trends of CO_2 emissions are evaluated from the consumption of clinker, thermal energy and electric energy in the process of cement making. It is assumed that in making one tonne of cement 110 GWh of electric energy and 3.4 Gj of thermal energy are consumed in the dry process technology CII (1995) and TEDDY (2000/2001). In the recent advanced energy efficient systems 2.9 GJ is consumed per tonne. We have accounted for this in the policy options.

Estimates are made for the availability of fly ash and blast furnace slag in India. The projections of coal consumption in thermal power plants and the pig iron production in steel making are utilised for the estimates. Availability of the blending materials is evaluated from the projections. These projected trends are used as feedback for making modifications in the structural composition of cement and (reduced) CO_2 emissions are calculated.

3.2. Modified scenarios

Population growth rate was chosen to build two modified scenarios. In scenario 1 (S1) the population growth rate is assumed to reach zero in the year 2020 and beyond, whereas in scenario 2 (S2) the population is assumed to stabilise by the year 2011.

The cement demand and production in these scenarios are balanced by appropriately stepping down the rate of cement production. Moreover, various technological policy options based on energy management, structural management and a combination of them are evaluated for the baseline and modified scenarios. The alternate policy options are made effective from the year 2006 except for the renewable energy option, which is incorporated from the year 2010.

Four sub parts are associated with the energy management scenario, i.e. use of renewable energy, waste heat recovery, improved specific energy consumption and a combination of all three of them. Specifically, the quantitative estimates adopted in our model are as follows:

(a) 25% of the electric energy required in cement plants is obtained from the renewable energy resources. This is not yet possible and is, therefore, implemented from the year 2010.
(b) The specific energy consumption (SEC) in Indian cement plants is 3.06 – 3.4 Gj/tonne, while in the advanced energy efficient plants it is as low as 2.9 Gj/tonne (Somani and Kothari, 1997; Schumacher and Sathaye, 1999; Price et al., 2000; Khurana et al., 2002). Therefore, the model is also run for the increased thermal energy efficiency up to 2.9 Gj/tonne of clinker produced.
(c) A scenario is generated where 30% of the thermal energy used is obtained from waste heat recovery.
(d) A combination of all the above-mentioned options is worked out.

The model is run for each of these options separately under the BS, S1 and S2 scenarios.

In the structural management scenario, the share of blended cement is increased keeping in view the availability of blending material. A scenario is generated taking into account the production of 37% OPC, 45% PPC, 16% PSC and 2% zeolite blended Portland cement.

Indirect CO_2 emissions resulting from the transportation of raw materials and the finished product are also considered for all the scenarios. We have taken the typical distance between the coalmines and cement industry as 1500 km, between the limestone mines and the cement industry as 200 km and between the cement industry and the user market as 250 km. Further, it is assumed that 55% of the raw materials and finished products are transported by rail and 45% are transported by road. These are tentative figures to determine the trends using the SD approach. Realistic figures could vary depending on the siting of the plants in the time to come.

4. Model validation

Confidence in the SD model for the system under study is established through its validation on the basis of the data utilized. The validation is carried out under three categories, viz. historical validation of the data, a structural verification test and a dimensional consistency test.

For the historical validation the cement production variable is selected. Data for the year 1990 is incorporated in the model and projections are made up to the year 2003. The model results give good agreement with the actual values, as is shown in Fig. 3. Points representing the actual and model values of cement production show an overall increasing trend. However, in the year 2000–2001, actual annual production was negative. The fall in growth rate is attributed to a recession in the demand (IIC, 2002), which subsequently attained a positive growth.

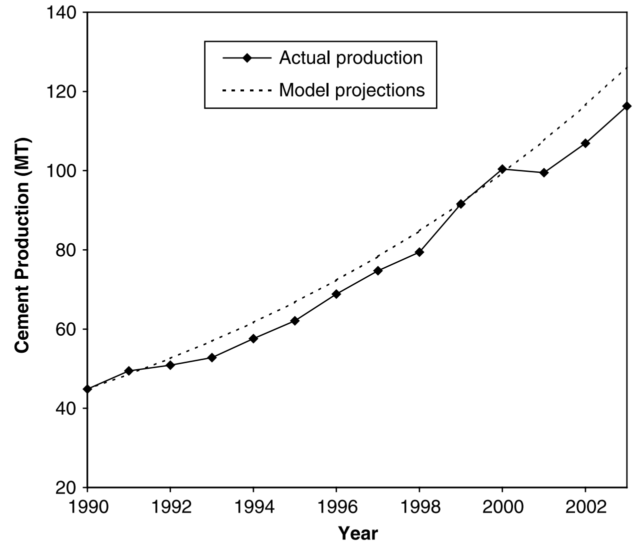

Fig. 3. Comparison of the quantity of cement production with the model projections.

The structural validation tests are applied at every stage of the model building process to detect any structural flaws in the model. These tests were, therefore, made simultaneously throughout the model building process. Initially, the model projected total population keeping the present rates of population growth and then switched over to the zero population growth rates by the years 2020 and 2011 for the population stabilisation scenarios S1 and S2 respectively. This is verified in Fig. 4 from the results obtained by running the model.

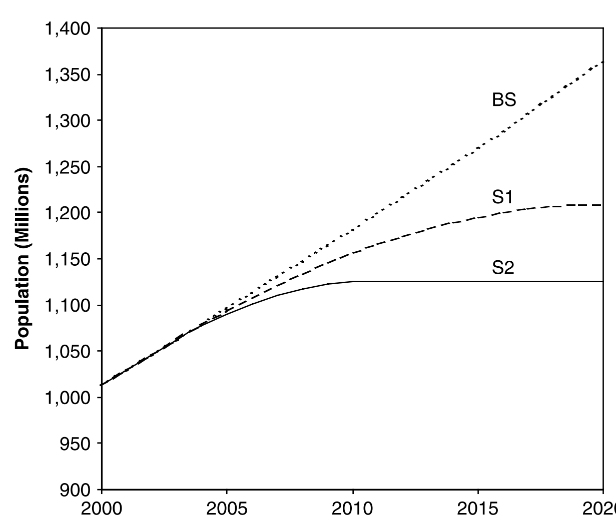

Fig. 4. Projections for population of India under the baseline scenario (BS), scenario 1 (S1) and scenario 2 (S2).

5. Sensitivity analysis

Sensitivity tests basically ascertain whether or not minor shifts in the model parameters can cause shift in the behaviour of the model. Once the robustness of the model is ensured, the model can be used for policy making (Forrester, 1961; Mohapatra et al., 1994). As already discussed, the emissions of CO_2 from the cement industry are dependent on population, GDP, cement demand and production. The sensitivity of the model to these parameters is described in the following sections:

5.1. Impact of population on cement demand

Population is considered to play an important role in controlling the cement demand, which in turn is the prime determinant for the production of cement and the ultimate CO_2 emissions from the cement plants. It is evident from Fig. 5 (a) that the population of the country would rise to 1421.80 million from the projected figure of 1364.50 million, by the year 2020. These calculations are made by changing the population growth rate multipliers from 1.57, 1.50 and 1.44 to 1.63%, 1.7 and 1.76% for the years 2001–2006, 2006–2011 and 2011–2018, respectively.

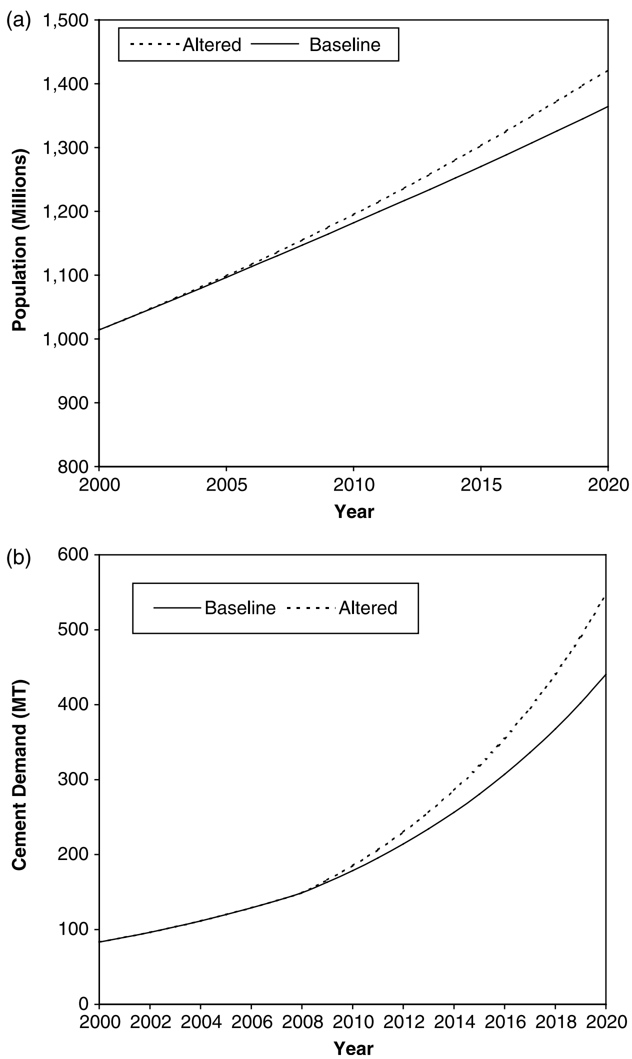

Fig. 5. Sensitivity of the model to the different parameters. (a) Impact of population growth rate multiplier on population. The population growth rate multiplier is changed from 1.57, 1.50 and 1.44% to 1.63, 1.7 and 1.76% for the years 2001–2006, 2006–2011 and 2011–2018, respectively, for obtaining the altered scenarios and (b) variation in cement demand with gross domestic product (GDP). The GDP is raised to 0.1 from 0.08 for the years 2008 onwards for obtaining the altered scenarios.

5.2. Impact of GDP on cement demand

The impact of GDP enhancement on cement demand is tested by raising the GDP to 0.1 from 0.08 for the years 2008 onwards. Fig. 5(b) shows the baseline and the altered curves. A small increase in GDP does contribute to the increased cement demand.

The model is thus sensitive to minor shifts in the parameters ensuring its clearance of the sensitivity test.

6. Results and discussion

The results obtained for different scenarios developed in the SD model are discussed to ascertain the impacts of various policy options on CO_2 emissions from the cement industry in India. Trends are evaluated for a 20 year span starting from the year 2000.

6.1. Baseline scenario

The rates of population growth and GDP as applicable in the year 2000 (GOI, 1997, 2001–2002) were kept constant for working out the baseline scenarios. The technology employed in making cement was also kept unaltered. Using these options, India's population is projected to reach 1364.50 million by the year 2020. Fig. 4 shows the population growth for the baseline (BS) and scenarios S1 and S2. The cement demand and cement production are shown in Fig. 6. Cement demand projected for

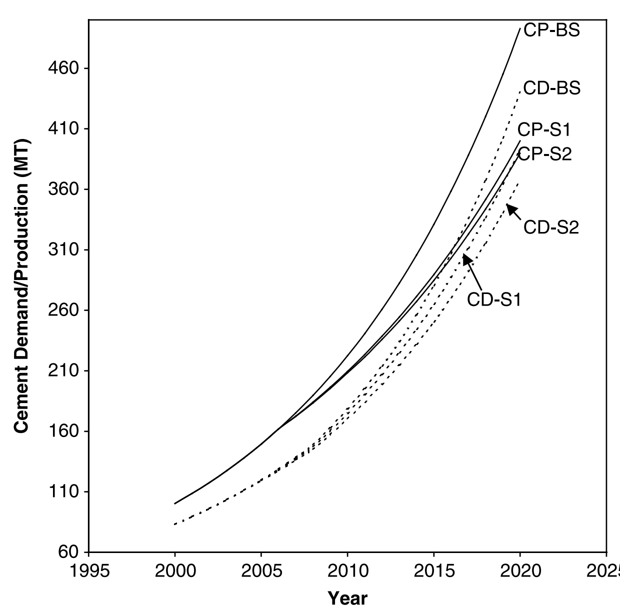

Fig. 6. Projections for cement demand (CD) and cement production (CP) for the baseline scenario (BS), scenario 1 (S1) and scenario 2 (S2).

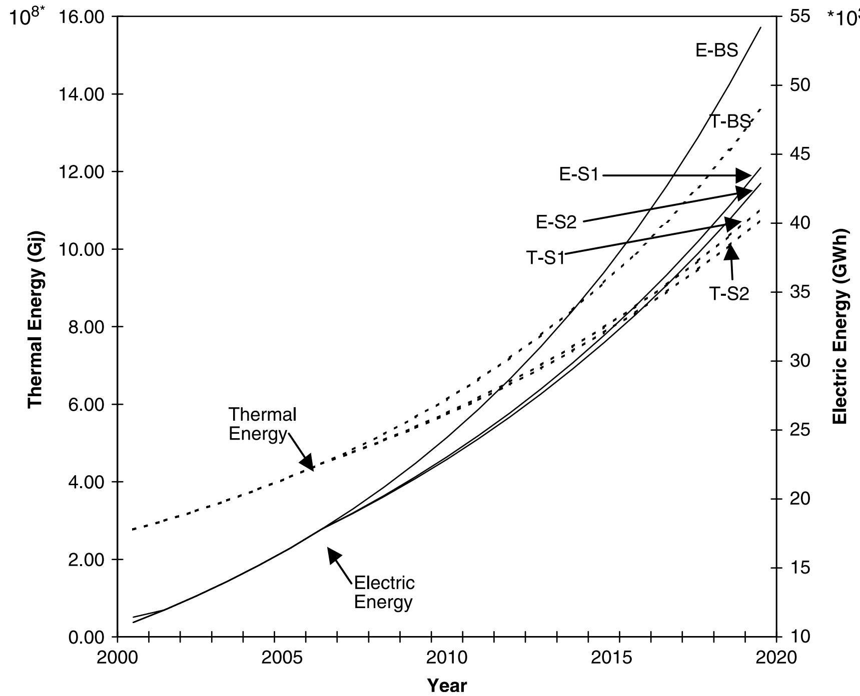

Fig. 7. Projections for thermal (T-BS, T-S1/S2) and electric (E-BS, E-S1/S2) energy consumption for the baseline scenario (BS), scenario 1 (S1) and scenario 2 (S2).

the year 2011 by our model is 195.50 million tones, and this is comparable to that of Schumacher and Sathaye (1999) (200.5 million tones). The cement production is projected to reach 492.83 million tonnes by the year 2020 with 331.13 million tonnes of OPC, 108.18 million tonnes of PPC and 53.52 million tones of PSC. The clinker requirement will be 400.95 million tonnes with respective shares of 314.58 million tonnes for OPC, 70.31 million tonnes for PPC and 16.06 million tonnes for PSC.

For the baseline scenarios the model has predicted that in the year 2020, 13.59×10^8 Gj of thermal energy and 54211.49 GWh of electric energy will be required in the making of cement. The respective CO_2 emissions will then be 135.92, 44.45 and 216.51 million tonnes from thermal energy consumption, electric energy consumption and clinker consumption. Figs. 7 and 8 show the annual growth of energy utilization, clinker consumption and total CO_2 emissions, respectively, for the BS and modified scenarios S1 and S2.

The direct CO_2 emissions are estimated to increase from 80.85 million tonnes in the year 2000–396.88 million tonnes in 20 years.

6.2. Modified scenarios

The cement demand and production are obviously linked to the population growth, economic activity in the country, the level and growth of GDP and the level of urbanization. Control of the population growth can be one of the options for mitigating the CO_2 emissions. As mentioned earlier, we have analysed two scenarios. In scenario 1 the growth rate for population is brought to zero by the year 2020 (S1) and in the scenario 2 (S2) a faster decline in the growth rate is analysed where zero growth rate is achieved in the year 2011.

Fig. 4 shows that with the S1 scenario the population of India would reach 1208.38 million in the year 2020. The cement demand will then be 393.31 million tonnes, a reduction of 10.67% from the base line scenario. This is shown in Fig. 6. Since the cement production is linked to its demand, which in turn is linked to population growth, a reduction of 18.81% in production is projected as compared to the baseline scenario. To produce the required quantity of cement (400.12 million

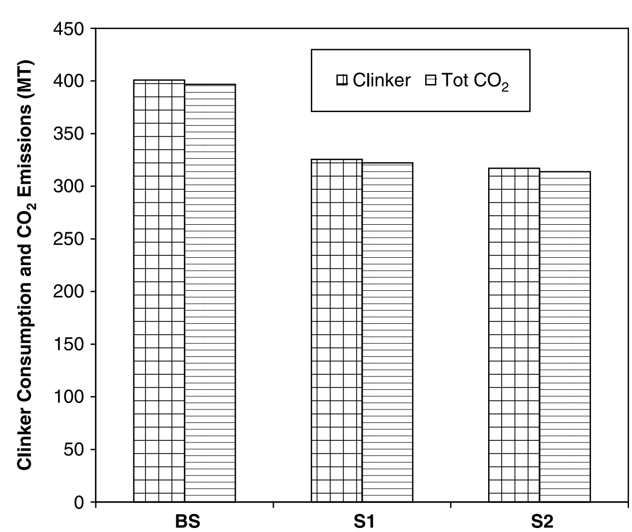

Fig. 8. Projections for clinker consumption for cement production and total CO_2 emissions from the cement industry under the baseline scenario (BS), scenario 1 (S1) and scenario 2 (S2) for the year 2020.

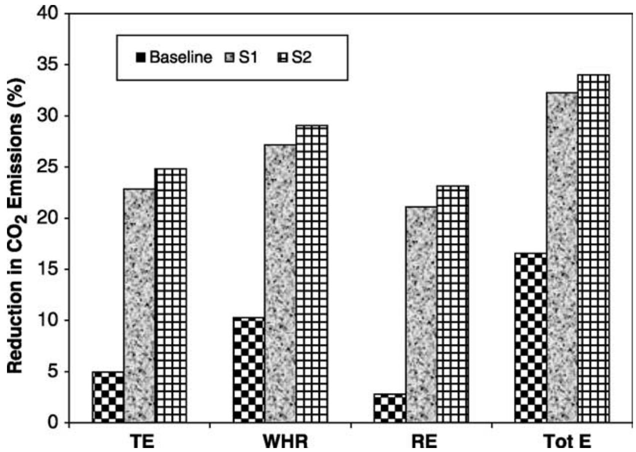

Fig. 9. Per cent reductions in CO_2 emissions from cement industry for the energy efficiency improvement (EEI) scenarios; 25% contribution of electric energy from the renewable sources of energy (RE) starting from the year 2010, 30% thermal energy recovery from waste heat (WHR), 2.9 Gj/tonne specific energy consumption (T) is used in clinker processing and a combined scenario taking all the above mentioned energy efficiency improvement scenarios (TotE). The baseline scenario (BS), scenario 1 (S1) and scenario 2 (S2) are shown separately.

tonnes), the consumption of thermal energy will be 11.04×10^8 Gj, electricity 44012.70 GWh (Fig. 7) and the clinker requirement will be 325.52 million tonnes (Fig. 8). As shown in Fig. 8, 322.22 million tonnes of CO2 will be emitted in the year 2020 from a combination of thermal energy consumption (110.35 million tonnes) electricity consumption (36.09 million tonnes) and clinker consumption (175.78 million tonnes). A further decrease in all the parameters, shown in Fig. 6–8, obviously occurred when we tried to stabalise the rate of population growth to zero by the year 2011 (S2). With the scenario S2 the population would stabalise at 1125.30 million by the year 2011 and, therefore, remain constant. A reduction of 20.92% (389.74 million tonnes) in cement production is projected for the year 2020 when applying the S2 policy option. Accordingly, the consumption of thermal energy will be 10.75×10^8 Gj, electricity use will be 423871.48 GWh and 317.08 million tonnes of clinker will be required. The corresponding CO_2 emissions will be 107.49 million tonnes due to thermal energy consumption, 35.15 million tonnes from electricity consumption, and 171.22 million tonnes in the calcination process. In total a 20.92% (313.87 million tonnes) reduction in direct CO_2 emissions will occur. When we reduce the rate of population growth, a decrease obviously occurs in the cement demand and production. But, the decline in cement demand does not follow the trend of population decrease, as the cement demand is linked to the investment in the cement-intensive infrastructure. India being a developing country such an investment will increase.

6.2.1. Energy management scenario

Fig. 9 shows the outcome of the energy management policy options for the BS and S1 and S2 scenarios. If 30% thermal energy from the waste heat is taken into account, the CO_2 emissions would decline to 356.11, 289.12 and 281.62 million tonnes for the BS, S1 and S2, respectively. The CO_2 emissions would be substantially curtailed by meeting some of the electric energy demand in the cement plants with renewable energy. It is expected that the renewable energy resources will play an important role in the years to come. For analyzing the effect of renewable energy we have replaced 25% of the electric energy supply to the cement plants with renewable energy. This is incorporated from the year 2010 since the electric power generation from renewable energy resources is expected to play a substantial role by that time. Reductions of 2.80% for BS, 21.09% for S1 and 23.13% for S2 in CO_2 are projected under these conditions. It is worth mentioning here that four cement plants in the Southern part of India have already installed 80.25 MW (e) capacity wind power generators in their wind farms. Presently they feed their output into the grid (www.cleantechindia.com/eicnew/cement.html).

Energy efficient clinker making technology is now available. When the improved specific energy consumption of 2.9 Gj/tonne of clinker production in the plant for the best practice technology (Schumacher and Sathaye, 1999; Price et al., 2000) is considered, CO_2 emissions are reduced by 4.95, 22.83 and 24.83% for the BS, S1 and S2. Fig. 9 also shows the percent reductions in theCO_2 emissions for an integrated scenario where all the above-mentioned energy management options are implemented simultaneously.

Table 1
Projections of CO_2 emissions due to clinker consumption for increasing share of Ordinary Portland Cement (OPC), Portland Slag Cement (PSC) and Portland Pozzolana Cement (PPC) for the baseline scenario

Year	Availability of blending materials (million tonnes)		Share of cement types (million tonnes)			CO_2 emissions from clinker consumption (million tonnes)
	Fly ash	Slag	OPC	PSC	PPC	
2000	28.15	15.91	67.46	10.90	22.04	44.11
2005	36.76	21.41	100.41	16.23	32.80	65.65
2010	48.00	28.81	149.46	24.16	48.83	97.72
2015	62.67	38.78	222.47	35.96	72.68	145.46
2020	81.83	52.19	331.13	53.52	108.18	216.51

WHR, Waste heat recovery; in this scenario 30% of the thermal energy is recovered from the waste heat. SM, Structural management; in this case the share of blended cement is increased to 37% OPC, 45% PPC, 16% PSC and 2% ZP.BS, Baseline scenario. S1, Population growth is stabilised to zero by the year 2020. S2, Population growth is stabilised to zero by the year 2011.The share of blended cements is ascertained from the availability of fly ash and slag.

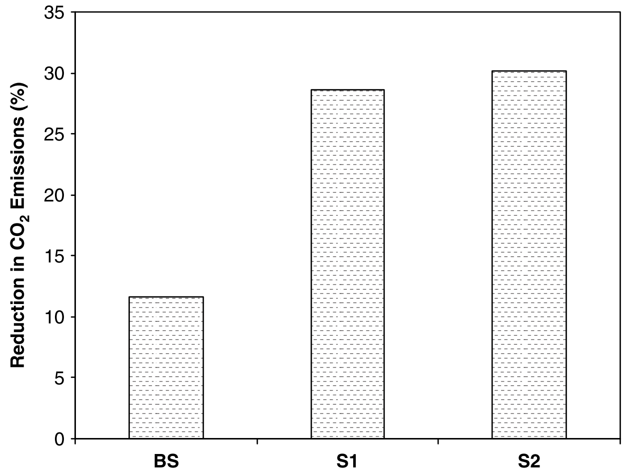

Fig. 10. Per cent reductions in CO_2 emissions for the structural management scenario under the baseline scenario (BS), scenario 1 (S1) and scenario 2 (S2).

6.2.2. *Structural management scenario*

For the structural management scenario the share of PPC has been increased to 45%, PSC to 16% and zeolite Portland to 2%. Availability of fly ash and blast furnace slag would restrict the further increase of their share.

In India the coal consumption in thermal power plants was 234.6 million tonnes in the year 2000 and is projected to reach 681.92 million tonnes by the year 2020. Therefore, 28.15 million tonnes of fly ash was available for cement use in the year 2000, but actually merely 6.61 million tonnes was utilized. The fly ash demand in cement plants is projected to reach 66.53 million tonnes in the year 2020 and 81.83 million tonnes will be available. Table 1 gives the projections of the availability of blending materials and CO_2 emissions for structurally modified cement production. Pig iron production in the iron and steel industry was 20.5 million tonnes in the year 2000, thereby generating 15.91 million tonnes of blast furnace slag. This iron production would reach 67.25 million tonnes in the year 2020 generating 52.19 million tonnes of furnace slag. With the presently chosen policy options the cement industry would require 51.25 million tonnes of slag. This goes well with its availability.

Scenarios generated by enhancing the percentages in blended cement to 45% PPC, 16% PSC and 2% zeolite Portland lead to 333.69 million tonnes of clinker consumption and 11.81×10^8 Gj thermal energy consumption by the year 2020. This option amounts to 11.63% reduction in the CO_2 emissions for the baseline scenario. Along the same lines, a further reduction of 28.26 and 30.12% is expected for S1 and S2, respectively, as is shown in Fig. 10. A decline in the share of OPC production from 62% to 56% and increase in the share of PPC production from 26 to 32% has been reported for the year 2001–2002 (http://www.indiacements.co.in/industry-Ver2.asp). Thus the usage of blended cements can be increased.

Structural change is beneficial not only in reducing the limestone consumption and its inherent carbon release but also in reducing the energy related CO_2 emissions.

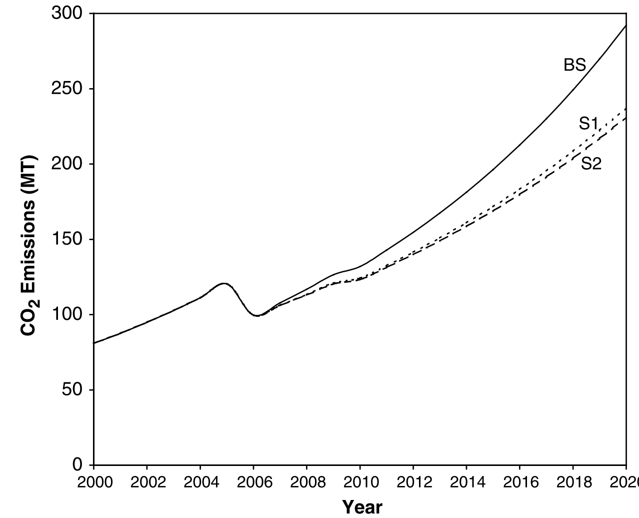

Fig. 11. Annual projections of the cumulative effect of the energy efficiency improvement scenario and structural management scenario on CO_2 emissions under the baseline scenario (BS), scenario 1 (S1) and scenario 2 (S2).

6.2.3. *Integrated scenario*

A combined scenario is generated by integrating the strategy of structural management (2% zeolite Portland, 45% PPC, 16% PSC and 37% OPC) and energy management (30% thermal energy recovered from waste heat, 25% of electric energy from renewable energy resources and taking 2.9 Gj/tonne specific energy consumption). For this integrated scenario, shown in Fig. 11, in the year 2020 the CO_2 emissions are projected to decrease by 26.37% (292.23 million tonnes), 40.22% (237.25 million tonnes) and 41.77% (231.11 million tonnes) for the BS,

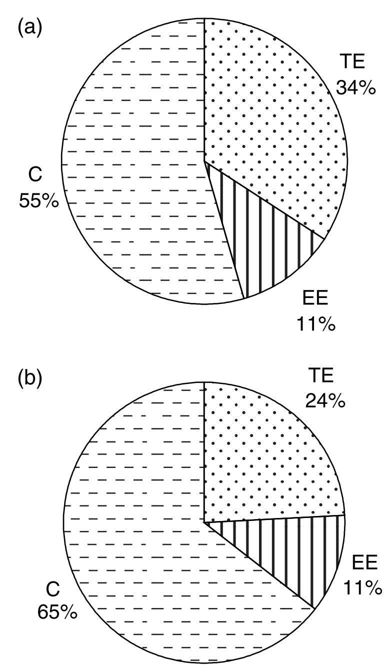

Fig. 12. Per cent share of CO_2 emissions from the use of clinker (C), electric energy (EE) and thermal energy (TE) for (a) the baseline scenario and (b) integrated scenario S2.

Table 2
Impact of policy options on the reduction of indirect CO_2 emissions from raw material (limestone and coal) transport to the cement plants

Policy options	Reduction of indirect (vehicular) CO_2 emissions from raw material transport (%)					
	Coal			Limestone		
	BS	S1	S2	BS	S1	S2
TEEI	14.41	30.50	32.35	0.0	18.80	20.93
WHR	30.00	43.13	44.65	0.0	18.80	20.93
SM	13.06	29.40	31.26	13.11	29.46	31.28
TEEI + WHR + SM	47.94	57.70	58.80	13.11	29.46	31.28

TEEI, Thermal energy efficiency improvement scenario where the specific energy consumption is decreased to 2.9 Gj/tonne cement production.

S1 and S2, respectively. There is a kink in Fig. 11 corresponding to the year 2006. This is due the incorporation of policy options implemented from the year 2006 (except for the 25% share from renewable energy). The renewable energy is made effective from the year 2010, which is evident in the form of another small kink.

Reductions in the CO_2 emissions are attributed to the combined effect of all the mitigation options. The shares of CO_2 emissions from the use of clinker, electric energy and thermal energy for the BS and S2 scenarios are shown in Fig. 12. In the case of BS, out of the total 396.88 million tonnes CO_2 emissions, 216.51 million tonnes comes from the clinker consumption. This is 55% of the total share. In the case of integrated scenario S2 the share of the CO_2 emissions (231.11 million tonnes) from clinker increases to 65%. However, the percent share of CO_2 emissions from the thermal energy reduces to 24% (55.46 million tonnes) for the integrated scenario S2.

6.2.4. Indirect CO_2 emissions

The indirect contribution to the CO_2 emissions from cement industry related operations comes from the fossil-fuel combustion in transporting the raw materials (coal and limestone) to the industry and the finished product cement to the market. For the year 2000, a total of 2.24 million tonnes of CO_2 is estimated to have been released in transporting coal to the cement industry. In this the share from road transportation is 2.01, and 0.40 million tonnes are from rail transport. This value is projected to reach 11.87, 9.64 and 9.39 million tonnes for the BS and S 1 and S2, respectively, by the year 2020.

The impact of policy options on the percent reduction of indirect CO_2 emissions from transport of the raw material (limestone and coal) to the cement plants is shown in Table 2. When the share of blended cement is increased, the coal transport related CO_2 emissions come down. On increasing the share of blended cement to 37% OPC, 45% PPC, 16% PSC and 2% zeolite Portland, emission reductions of 13.06, 29.46 and 31.26% for the BS, S1 and S2, respectively, are expected by the year 2020. This is due to the reduced fuel requirement in the case of blended cement. If the energy efficiency of the plants could be improved to 2.9 Gj/tonne of clinker, a maximum reduction of 32.35% in the CO_2 emissions for S2 is expected, due to lowering of the coal consumption. In a combined scenario of structural management and energy efficiency improvement, the CO_2 emissions from the coal transport come down by 58.80%. The CO_2 emissions from the transport of limestone to the cement plants are projected to reach 12.66, 10.28 and 10.01 million tonnes by the year 2020 for the BS, S1 and S2, respectively.

In the baseline scenario transport of cement to the market will contribute 12.16 million tonnes of CO_2 emissions by the year 2020. These emissions are estimated to go down to the respective values of 9.87 and 9.62 million tonnes for population growth stabalisation scenarios S1 and S2. Percent reductions of indirect vehicular CO_2 emissions from the transport of the raw materials (coal, limestone) to the cement plants and cement to the market are shown in Fig. 13.

Emissions from the transportation of the materials by road are obviously more than those by rail transport. Railways consume the least direct fuel energy per tonne kilometer and hence less CO_2 is emitted per tonne kilometer. A reduction of approximately 85% in the CO_2 emissions is estimated if the freight transportation is shifted from road to rail. Ramanathan and Parikh (1999) have reported that the energy consumption and CO_2 emissions per tonne kilometer by trucks are nearly five times the corresponding values for rail transport.

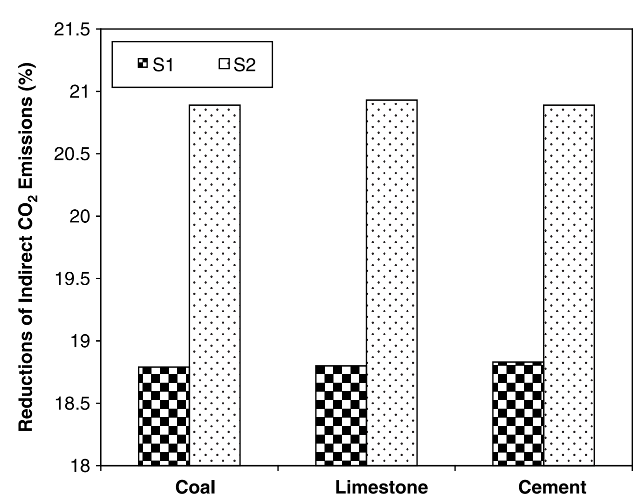

Fig. 13. Per cent reductions in indirect (vehicular) CO_2 emissions from transport of the raw material (limestone and coal) to the cement plants and finished product cement to market under the Scenario 1 (S1) and scenario 2 (S2).

7. Conclusions

A system dynamics model for the CO_2 emissions from the cement sector was developed. The model was applied to make projections of CO_2 emissions in India for a time span of 20 years. The cement production with the baseline scenario (present rate of population growth) is projected to contribute 396.89 million tonnes of CO_2 to the greenhouse gas load by the year 2020. Mitigation strategies for curtailing the CO_2 emissions from this sector are identified and analysed. The CO_2 emissions from cement plants are dependent on many interrelated variables, viz. population and GDP growth rate, cement demand and production, clinker consumption and energy utilized. Quantitative estimates of CO_2 emissions due to stabilisation of the population growth, curtailment of excess cement production, structural management, energy efficiency management and a combination of all these measures have been worked out. A combined scenario with population stabilisation by the year 2010, structural shifting (2% zeolite Portland, 45% PPC, 16% PSC and 37% OPC), 25% contribution from renewable sources of energy for the cement industry starting from the year 2010, and use of an energy efficient process with 2.9 Gj/tonne specific energy consumption and 30% thermal energy recovery from waste heat can reduce the CO_2 emissions from the Indian cement industry by approximately 42% in the year 2020. This could be a substantial lowering of the greenhouse gas load to the environment.

Indirect CO_2 emissions coming from the transportation of raw materials (coal and limestone) to the cement plants and finished products (cement) to the market were also worked out. The CO_2 emissions from road transport are more in comparison to that from rail transport. Thus, a shift from the use of trucks to the railways will also lead to a reduction in CO_2 emissions.

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