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RESEARCH PAPER

Dynamic Material Flow Analysis of Cement in Iran: New Insights for Sustainability of Civil Infrastructures

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ABSTRACT: In this article, a Dynamic Material Flow Analysis (DMFA) model is presented that characterizes the stocks and flows of cement from 1963 to 2063 in Iran. Using cement consumption data for the period of 1963-2018 an attempt is made to provide reliable estimates of the present as well as future cement in-use stocks and discards (from 2019 to 2063) to relevant stakeholders such as the Ministry of Road and Urban Development, Department of Environment, public and private utilities, and the construction and cement industries. Based on a normal lifetime distribution, a flow dynamic model is developed for each cement end-use category including buildings, infrastructures and others. Each sub model is simulated with 9 scenarios made from combinations of 3 scenarios for future cement consumption growth rate and 3 scenarios for the mean lifetime of the structures. For the base scenario, the model-derived estimate of in-use cement stock and cumulative discard for the year 2063 is 2191 million metric tons (Mt) and 1856 Mt, respectively. Such a great discard should be considered in policy making for better life cycle management of cement in Iran. The main finding of the paper is that by increasing the mean lifetime of the structures (especially buildings), the amount of cumulative cement discard in 2063 can be drastically decreased (generally over 50%) and this decrease will not be affected considerably by the cement consumption growth rate in the future. So this can be a reliable strategy for the sustainable life cycle management of infrastructures in Iran.

Keywords: Cement Discard, Cement Life Cycle, Dynamic Modeling, Material Flow Analysis (MFA), Normal Lifetime Distribution, Structures.

1. Introduction

According to Horvath (2004), optimum performance, extended useful life, minimum life-cycle costs, and minimal environmental life-cycle impacts, including the minimum use of virgin raw materials, are the main characteristics of sustainable infrastructure systems. The rate of accumulation of new stock, its characteristics in terms of material use and service life, and the renovation of existing stock are key determinatives of infrastructure sustainability.

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Cement is one of the most extensively used construction material for buildings and infrastructures in Iran. Better management of cement stock in the form of buildings, highways, bridges, and other infrastructures built up over the past years can influence the stocks and flows of cement discard in the future. The first step to do this is quantifying the stock of cement in-use. Static and dynamic modeling are the two basic approaches to quantifying stocks. In the dynamic approach, material inflows to the system boundary under consideration are categorized into different end-uses (for example the amount of cement used for residential, commercial, and public buildings). Each of the end-uses is assigned a service lifetime. The lifetime determines the delay between the material inflows and material outflows in form of discards. The difference between the material inputs and discards is the net addition to in-use stock. The static approach provides a single snapshot of stocks and flows, whereas the dynamic model can be used to characterize the net addition or depletion of stocks over time. Characterization of stocks over time can also be used to estimate future discards or emissions. Such information is useful to formulate end-of-life strategies and management systems (Kapur and Keoleian, 2009).

The general paradigm of modeling of dynamic MFA is either stock dynamic or flow dynamic. Flow dynamic models are based on the basic assumption that the inflow and outflow of material stock is its main driving force. The future amount of inflow is either assumed or estimated using socio-economic variables by different techniques; while the amount of outflow is calculated by a delay process using an assumed lifetime distribution. The other type of modeling approach is stock dynamics driving. Its basic assumption is that the stock of service units is the driver for the material flows. The stock can be calculated by assigning a ‘development pattern’, ‘stock expansion rate’ or can be formulated as a function of population and its lifestyle. The outflow of materials and its associated obsolete service units is determined by the delay process, while the inflow of materials and its associated new add-in service units is calculated to maintain the development pattern of stock in use (Müller et al., 2006)

The purpose of this study is to characterize the stock and flow of cement from 1963 to 2063 in Iran. In this research, a flow dynamic driving model is developed for cement to characterize the stock and flows of cement from 1963 to 2063 in Iran. Thus the model has a retrospective and prospective approach. The driving force of the model is the cement inflow that is determined from 1963 to 2018 from the existent cement consumption statistics and extrapolated for the period 2019-2063 by a constant consumption growth rate (for different scenarios). A normal distribution function is used for the life time of different end uses. The information derived from the model is important for different stakeholders in Iran’s infrastructure to make decisions about buildings and infrastructures more sustainable.

2. Literature Review

Table 1 presents a literature review of the most related dynamic MFA for construction materials and thus does not cover the wide range of dynamic MFA papers. The review is structured in three parts (the first row of Table 1); model type, model features and case study. In model type, it is showed that the general paradigm of modeling of dynamic MFA is either stock dynamic or flow dynamic. Flow dynamic driving, as applied in Kleijn et al. (2000), Kapur et al. (2008), Cao et al. (2017) and Miller (2020) assumes that the material stock is driven by its inflow and outflow. Stock dynamics driving approach has been presented in Müller et al. (2004), Müller (2006), Bergsdal et al. (2007), Sartori et al. (2008), Hu et al. (2010a), Huang et al. (2013) and Cao et al. (2018).

Table 1. Literature review of the most related dynamic MFA for construction materials

Reference	**Type of model**	**Model features**					**Case study**	
	Stock / Flow dynamic	**Lifetime distribution**	**Retrospective / Prospective**	**Recycling/ Renovation**	**Environmental impacts**	**Scenario analysis/ Sensitivity analysis/ Uncertainty analysis**	**Material/ Substance**	**Country**
Kapur et al. (2008)	Flow dynamic	Gamma, Weibull, LogNormal	Retrospective	Recycling	-----	No scenario, Monte Carlo method for uncertainty considerations	Cement (all sectors)	USA
Hu et al. (2010a)	Stock dynamic	Normal	Retrospective and prospective	Recycling	CO_2 emissions, net steel use	Material intensity, mean life time, floor area, recycling	Steel and iron in residential buildings	China
Huang et al. (2013)	Stock dynamic	Normal	Retrospective and prospective	Recycling	CO_2 emissions, iron ore, limestone, solid waste	Mean life time, recycling	Steel, glass, wood, gravel, sand, lime, brick, cement in buildings	China
Müller (2008)	Stock dynamic	Normal	Retrospective and prospective	----	----	Mean life time, material intensity, floor area	Concrete in dwelling stock	Netherland
Müller (2004)	Stock dynamic	Normal	Retrospective and prospective	----	Energy supply, waste	----	----	Swiss
Bergsdal et al. (2007)	Stock dynamic	Normal	Retrospective and prospective	----	----	Material intensity, mean life time	Concrete and wood in dwelling stock	Norway
Sartori et al. (2008)	Stock dynamic	Normal	Retrospective and prospective	Renovation	----	Person per dwelling, size of the dwelling, population, the interval of renovation	The stock of floor area (no material)	Norway
Cao et al. (2017)	Flow dynamic	Normal, Weibull	Retrospective: 1920-2013	----	----	Parameters of life time distribution, production data, sector split ratio	Cement in building, infrastructure and agriculture	China
Cao et al. (2018)	Stock dynamic	Weibull	Retrospective and prospective: 1985-2100	----	----	Parameters of life time distribution, Material intensity , Floor area, urbanization rate, population	Cement, steel, wood, brick, gravel, sand in the housing sector	China
Miller (2020)	Flow dynamic	Gamma, Weibull, LogNormal	Retrospective:	Recycling	-----	No scenario, Monte Carlo method for uncertainty considerations	Cement (all sectors)	USA
This paper	Flow dynamic	Normal	Retrospective and prospective: 1963-2063	----	----	Mean life time, consumption growth rate	Cement (all sectors)	Iran

In columns with header “model feature” different aspects of modeling are determined including: the type of life time distribution, time dimension, considering recycling and/or renovation in the model, considering environmental impacts, and scenario analysis, sensitivity analysis, and uncertainty analysis. The lifetime distribution function most frequently used in the area of dynamic MFA for construction material is a normal distribution. Most reviewed articles in Table 1 used a retrospective and prospective approach i.e. models the stock and flow both for the past and future. Some of them used only the retrospective approach and does not include any forecasting for the future. Few studies consider recycling, renovation and environmental impacts as features of the model. The scenario analysis or sensitivity analysis is a common part of almost all papers. The life time distribution and material intensity are the two main factors for a scenario or sensitivity analysis. In the last two columns, the specifications of the case study are presented which include the type of material or substances and the spatial scale of the case study. Some papers consider only a substance such as cement and others investigate a combination of construction materials such as concrete, steel, glass, wood etc. Finally, all of the papers presented in the table include a case study at the national level. The last row of Table 1 shows the characteristics of this research. The details of the model will be presented in the next section.

The main focus of the model is twofold: 1) Estimating the in-use cement stock for the present as well as future. This estimate will provide a foundation for policy design for better management of this stock to postpone its discard and reduce demand for new cement; 2) Estimating cumulative cement discard (or waste) for the present and the future. Such estimation would be critical to better design of demolition waste management strategies.

There are many studies in the context of Construction and Demolition (C&D) waste management that are related to this research. In fact, one of the main aspects of the researches in dynamic MFA for construction materials is to estimate the stock of waste. Some studies only estimate the waste of demolition as the main outflow of the dynamic MFA model (e.g. Muller, 2006; Kapur et al., 2008). Some papers estimate both construction and demolition waste. For example Huang et al. (2013) estimated demand for materials and environmental impacts of buildings in China from 1950 to 2050 based on the dynamic MFA. They studied the effect of lengthening the lifetime of buildings and enhancing materials recycling on reducing demand for raw material, generation of solid waste and CO_2 emissions. Hu et al (2010b) studied the construction and demolition flow of housing floor areas and the consumption and waste flows of concrete for Beijing from 1949 through 2050. Their findings indicated that C&D waste generation in the near future strongly depends on the lifetime of the buildings. They concluded that if the buildings lifetime can be extended, sever demolition pressure can be postponed or even reduced totally. It is worth noting that only in the stock dynamic models it is possible to calculate C&D waste generation.

As mentioned before, in the stock dynamic models, the stock of service units (buildings and infrastructures) is the driver for the material flows. So, the flow of all related materials (construction materials and waste) can be tracked and calculated. But in the flow dynamic models that material stock is driven by its inflow, only the flow of a single substance (for example cement or steel) can be tracked and thus all related C&D waste cannot be calculated. Only waste from the mentioned substance can be estimated after stock useful life.

There are also some researches in C&D waste literature that are based on the static MFA. One can refer to Condeixa et al. (2017), Wiedenhofer et al. (2015), Surahman et al. (2017), Wang et al. (2018)

and Huang et al. (2018). An analytical review of different methods for quantifying construction and demolition waste can be found at Wu et al. (2014). This research, from the viewpoint of waste context, only considers the demolition waste, i.e., the only waste in the model developed is the outflow of in-use cement stock which is derived by the lifetime of the stock. Even the only demolition waste in our model is cement discard. Other wastes materials arising from demolition are not the output of the model. This is because our model is a flow dynamic substance flow analysis model that tracks the flow of cement and ignores other related construction material in the building lifecycle. No construction waste is also calculated and thus this research is not completely fitted to the C&D waste context. So the literature review table was confined to the most related papers in the context of dynamic MFA.

3. Methodology and Data

3.1. Cement Life Cycle

The generic life cycle of cement has three life stages of production (including extraction of raw material), use, and waste management at the end of life. Figure 1 shows a generic view of cement life cycle. At every stage of the life cycle there can be material exchanges with the lithosphere, environment, and material imports and exports.

3.2. Goal, Scope and Features of the Model

The model described below does not include the production and end of life stage of the mentioned life cycle. It means that the capacity constraints of the production and different scenarios of the end of life are not considered in the model. Thus the model is an open loop one and does not include reverse flows (recycling). Repair and renovation will not also be considered in the model. The model uses the historical and extrapolated data of cement inflow to estimate the stock of cement discards. The stock of cement in-use is the other result of this calculation process.

The time scope of the model consists of two parts. The first part is the interval 1963-2018 when the historical data of cement consumption is used as the driver of the model. The second part is the interval 2019-2063 when the extrapolated data of cement consumption under different scenarios are used to estimate the stock of in-use and discards.

The model is disaggregated to different cement end-uses including “buildings” (residential, commercial and public), “infrastructures” (roads, bridges, highways, water and wastewater infrastructures, etc.) and “other” uses (farms, parks, stadiums, mines, etc). The main reason for such classification is its suitability for data gathering about cement end-use market share. Cement consumption growth rate, the mean and standard deviation of lifetime distribution are the main parameters of the model that directly affect the calculated stock. As will be described later, different scenarios for these parameters are used to better predict the future stock of cement in-use and discard. Because of the lack of data about the most appropriate life time distribution of different end uses, a normal distribution function is used for all of them.

3.3. Basic Structure of the Model

The model presented herein represents a Dynamic Material Flow Analysis (DMFA) of cement. It is based on the flow dynamics approach. Figure 2 illustrates the main aspects of the model. Processes are illustrated by rectangles, flows by ovals, and drivers and determinants by hexagons. Arcs represent influences between variables. The stock of in-use cement is denoted by M and the net stock accumulation by dM/dt. The input flow to the stock is given by dM_{in}/dt, while the output flow is represented as dM_{out}/dt. Determinants are denoted as F(t) for cement consumption, and L for the end-use lifetime (i.e. life time of buildings, infrastructures and others).

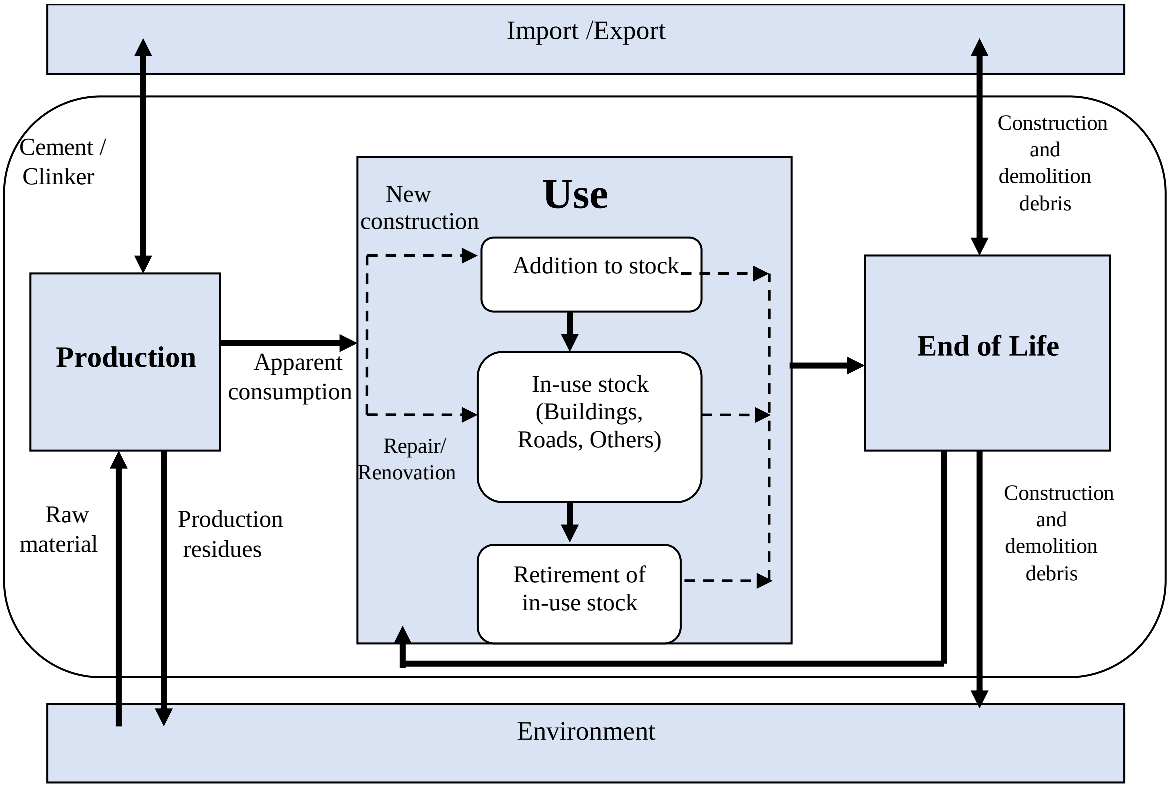


Fig. 1. Generic cement life cycle (adopted from Kapur et al., 2008)

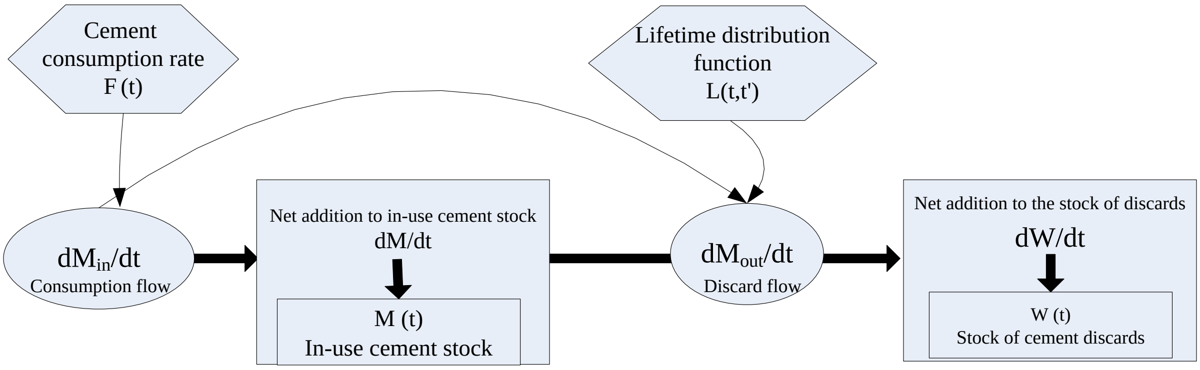


Fig. 2. Basic cement flow dynamic model

3.4. Model Formulation

According to Hu et al. (2010a), the flow dynamic model with some modifications can be described mathematically with a system of five differential equations as follows:

Eq. (1) defines the driver of the model (that is the cement inflow). The stock of in-use cement is driven by the cement consumption (here F(t)).

Eq. (2) defines the delay character of the cement stock in use. The outflow of the cement stock is determined by the previous inflow by delaying it by an assumed service lifetime. Since different infrastructures may have different service lifetimes before they are demolished, a lifetime distribution L(t, t') is used in Eq. (2), representing the probability that the structure units entering service at the time t' are going to be removed from the stock at the time t.

Eq. (3) defines a normal lifetime distribution L(t,t') for the model, with mean lifetime μ and standard deviation σ. Eq. (4) represents that the cement stock in the system can be calculated according to the material inflow and outflow. Finally, Eq. (5) describes that net addition to the stock of cement discards is equal to discard flow considering no outflow from this stock (for example by recycling).

It is worth noting that a discretized version of this continuous-time differential equation system should be used in practice.

Since the yearly data for cement consumption are available and because of the wide time range of this analysis it is rational to consider one year as the time step for the discrete form model. Such a model was formulated in Microsoft Excel and used for calculations.

$$\frac{\mathrm{dM_{in}(t)}}{\mathrm{dt}} = F(\mathrm{t}) \tag{1}$$

$$\frac{\mathrm{dM_{out}(t)}}{dt} = \int_{t_0}^{t} \mathrm{L(t,t')}.\frac{\mathrm{dM_{in}(t')}}{\mathrm{dt}}\mathrm{dt'} \tag{2}$$

$$\mathrm{L(t,t')} = \frac{1}{\sigma\sqrt{2\pi}}.\mathrm{e}^{-\frac{(t-t'-\mu)^2}{2\sigma^2}} \tag{3}$$

$$\frac{dM(t)}{dt} = \frac{\mathrm{dM_{in}(t)}}{\mathrm{dt}} - \frac{\mathrm{dM_{out}(t)}}{dt} \tag{4}$$

$$\frac{dW(t)}{dt} = \frac{\mathrm{dM_{out}(t)}}{dt} \tag{5}$$

in which $M(t)$: is the stock of in-use cement (million metric tons), $\frac{dM_{in}(t)}{dt}$: is the rate of inflow to the stock of in-use cement (million metric tons/year), $\frac{dM_{out}(t)}{dt}$: is the rate of outflow from the stock of in-use cement (discard flow) (million metric tons/year), $\frac{dM(t)}{dt}$: is the rate of net addition to the stock of in-use cement (million metric tons/year), $W(t)$: is the stock of cement discard (million metric tons), $\frac{dW(t)}{dt}$: is the rate of net addition to the stock of cement discard (million metric tons/year), $F(t)$: is the cement consumption rate, $L(t,t')$: is the lifetime distribution representing the probability that the structure units entering service at the time t’ are going to be removed from the stock at the time t, σ: is the standard deviation of lifetime of infrastructure (year) and μ: is the mean of lifetime of infrastructure (year).

3.5. Scenario Planning and Simulation

There is large uncertainty in the main parameters of the model i.e. lifetime distribution parameters and cement consumption rate. The prediction of cement consumption rate for the interval 2019-2063 consists of inevitable uncertainty. Concluding from some researches on the perspective of Iran cement industry (The Global Cement Report, 2017; Edwards, 2017; Namazi and Bastami, 2019) three scenarios for the growth of cement consumption rate that are most likely in the future include high (5%), medium (3%) and low (1%) which is depicted in the first row of Table 2. From another way it is reasonable to consider three scenarios for the mean lifetime of cement end-use: short, medium and long lifetime. The values of the mean lifetime for different end-uses are provided in the first column of Table 2. Symbols μ_B, μ_I, μ_O stand for mean lifetime of buildings, infrastructures and other end-use. The mean lifetime data are derived from various sources such as industry reports, research studies and government surveys. The combination of these values results in 9 scenarios for the model (S1-1 to S3-3). These scenarios are demonstrated in Figure 3 which includes three sub-models according to different end-uses. These three sub-models will be run separately and then aggregated stocks of cement in-use and cement discard are calculated by summing of corresponding stocks of these sub-models. Because of the lack of data and any estimation, for all scenarios, the standard deviation of lifetime is considered to be 10 years, *i.e.* $\sigma = 10$. All sub-models formulated and simulated in Microsoft Excel.

Notably, the current trend in cement consumption in Iran implicates the low growth rate in cement consumption. In another way the short lifetime scenario represents the current situation in Iran. So S1-3 can be considered as the base scenario that represents the possible future if no significant changes will happen for the cement consumption growth rate and the average lifetime of structures.

3.6. Cement Consumption Data

Figure 4a shows the consumption of cement in Iran over the last 56 years (1963-2018). Over this period, the cumulative cement consumption in Iran was approximately 1137 Mt (beyond 1Gt). As seen in Figure 4a, both flow and stock of cement consumption have doubled approximately from 2005 to 2013. This is because of the large development of the cement production industry in Iran at this period and also considerable growth of construction both in the private and public sectors of Iran's economy. For example, a national project for constructing residential building for low income families called "Maskan Mehr" was performed at this period that included the construction of above 2 million units of residential buildings. Such projects considerably increased the consumption of cement in Iran. There is also a fall in cement consumption in 2012 as seen in Figure 4a. The cause of this fall is the economic recession in Iran and the consequent recession in the construction industry.

There is no reliable data on cement consumption before 1963 in Iran so it is eliminated from this analysis. It is worth noting that cement consumption in this analysis refers to internal consumption and exclude cement export. This is because of the goal of this study, i.e. estimating the in-use cement stock and the stock of cement discard in Iran. Figure 4b demonstrates three scenarios (introduced in Section 2.5) for the future cement consumption in Iran for the period 2019-2063. Considering the recent economic recession in Iran, the scenario with low cement consumption growth is more probable for near future. However, for the sake of comparative analysis and scenario-based planning, and the relatively wide time horizon of the study, scenarios with medium and high consumption growth are also considered in this study.

Cement consumption was divided into various end-use markets. Based on available data these markets in Iran were divided into three parts: buildings (residential, commercial, public), civil infrastructures (such as roads, highways, bridges, tunnels, dams, etc.), and others (farms, stadiums, mining, defense, etc.). Figure 5 shows the cement end-use market share in Iran in recent years based on available resources (Dorafshani, 1996; RHUDRC, 2019).

The building sector has the largest portion of the cement market (60%). Civil infrastructures with 28% have the second rank and other uses include the remaining 12 % of ultimate cement consumption. There is no historical data about the cement end-use market share during the last 56 years (1963-2018). There is also no estimation of this market share in the future. This research deals with this problem by assuming that the cement end-use market share does not change radically over the next several decades. So, the cement market share in recent years is used for the entire time horizon of the model i.e. 1963-2063. Future studies may improve the result of this study by providing an accurate estimate of future cement end-use market share.

4. Results and Discussion

4.1. Estimate of Stock of in-Use Cement and Cumulative Cement Discards in 2018

Table 3 and Figure 6 show cumulative cement consumption, stock of in-use cement and cumulative cement discards in 2018 for different lifetime scenarios. Since the cement consumption data for the period of 1963-2018 is based on real data so there is no scenario on cement consumption and the results are shown based on only lifetime scenarios. According to these results, cumulative cement consumption in 2018 was about 1137.55 Mt (Million metric tons) while the estimated stock of in-use cement differs from 946.42 Mt in the short lifetime scenario to 1108.46 Mt in the long lifetime scenario. This means that because of the lack of data on the real lifetime of buildings, infrastructures and other end-use of cement, there is no certainty about the real stock of in-use cement at 2018 but it is estimated to be around 1000 Mt (or 1Gt (rigatoni)). Also, the cumulative discard of cement varies from 191.13 in the short lifetime scenario to 29.09 Mt in the long lifetime scenario indicating there is large uncertainty in the present stock of cement discard in Iran.

Table 2. Different scenarios for mean lifetime and growth in consumption rate

Scenarios for growth in consumption rate **Lifetime scenarios**	**High consumption growth (5%)**	**Medium consumption growth (3%)**	**Low consumption growth (1%)**
short lifetime $(\mu_B = 30, \mu_I = 40, \mu_O = 20)$	S 1-1	S 1-2	S 1-3 (Base scenario)
medium lifetime $(\mu_B = 40, \mu_I = 50, \mu_O = 30)$	S 2-1	S 2-2	S 2-3
long lifetime $(\mu_B = 50, \mu_I = 60, \mu_O = 40)$	S 3-1	S 3-2	S 3-3

Table 3. Cumulative cement consumption, in-use and discards (million metric tons) at 2018 for different lifetime scenarios

Lifetime scenarios	**End-use category**	**Consumption**	**In-use**	**Discard**
Short lifetime $(\mu_B = 30, \mu_I = 40, \mu_O = 20)$	Buildings	682.53	561.10	121.43
	Infrastructure	318.51	293.84	24.68
	Others	136.51	91.48	45.02
	Aggregated	**1137.55**	**946.42**	**191.13**
medium lifetime $(\mu_B = 40, \mu_I = 50, \mu_O = 30)$	Buildings	682.53	629.65	52.88
	Infrastructure	318.51	310.63	7.89
	Others	136.51	112.22	24.29
	Aggregated	**1137.55**	**1052.50**	**85.05**
long lifetime $(\mu_B = 50, \mu_I = 60, \mu_O = 40)$	Buildings	682.53	665.63	16.90
	Infrastructure	318.51	316.90	1.61
	Others	136.51	125.93	10.58
	Aggregated	**1137.55**	**1108.46**	**29.09**

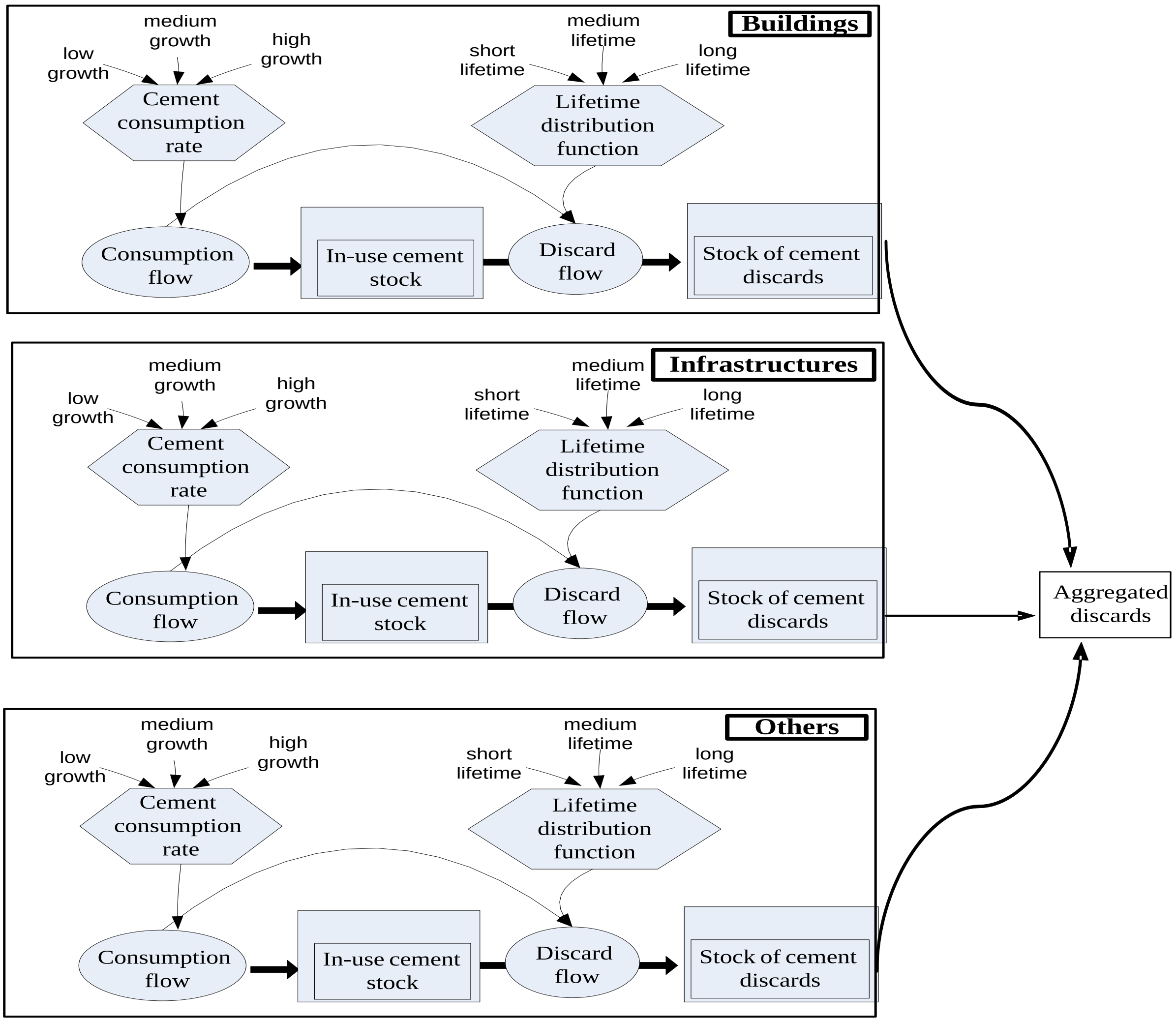
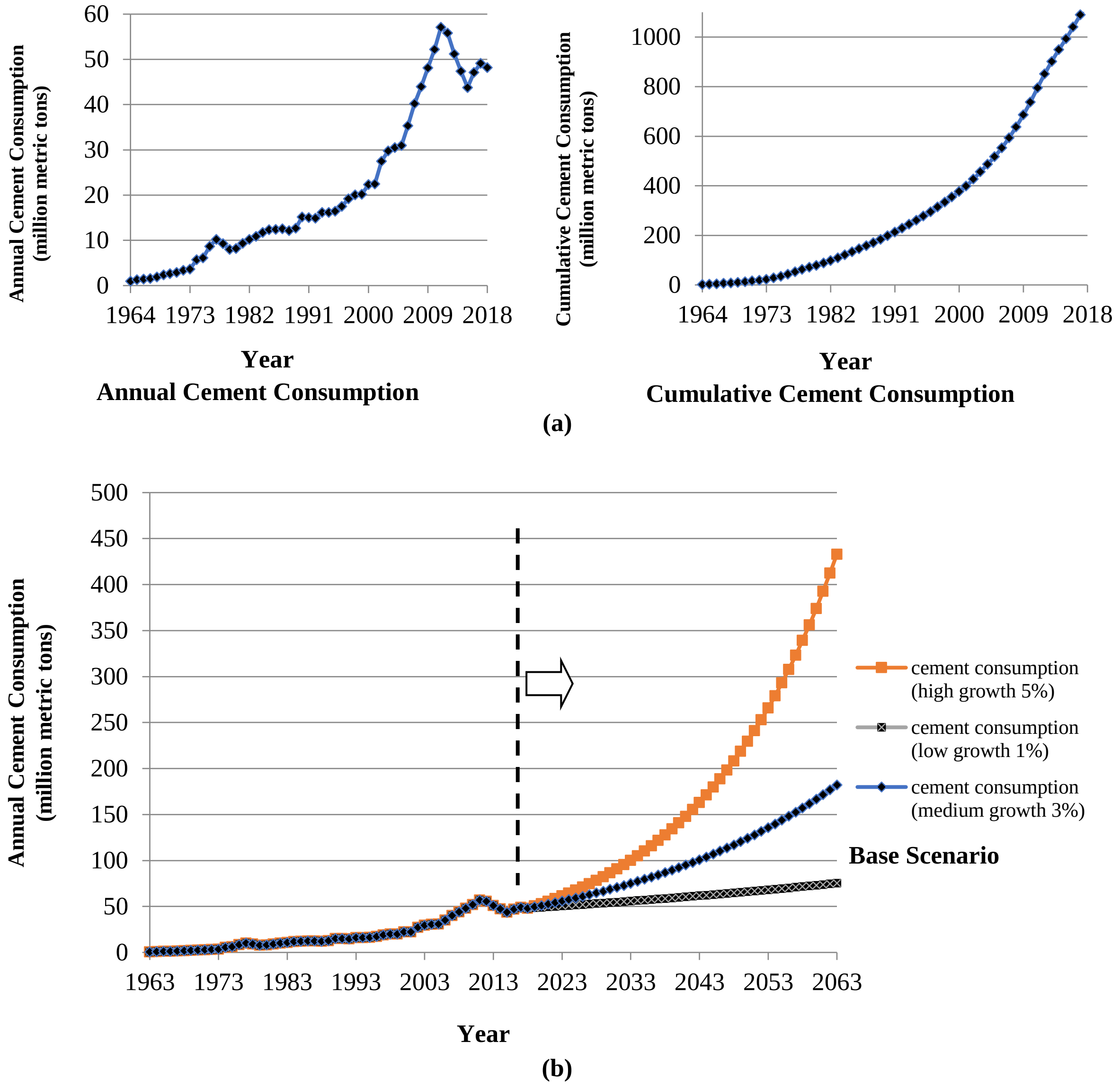


Fig. 3. Three sub-models (each one includes 9 scenarios) for cement flow dynamic model



(a)

(b)

Fig. 4. Historical data and future projection for cement consumption in Iran: a) Annual and cumulative consumption of cement in Iran over the last 56 years (million metric tons) (Data source: Iran Cement Statistics, 2019; Ahmadi and Karimi, 2015; Heibati and Farzin, 2005); and b) Three scenarios for annual future cement consumption in Iran (2019-2063)

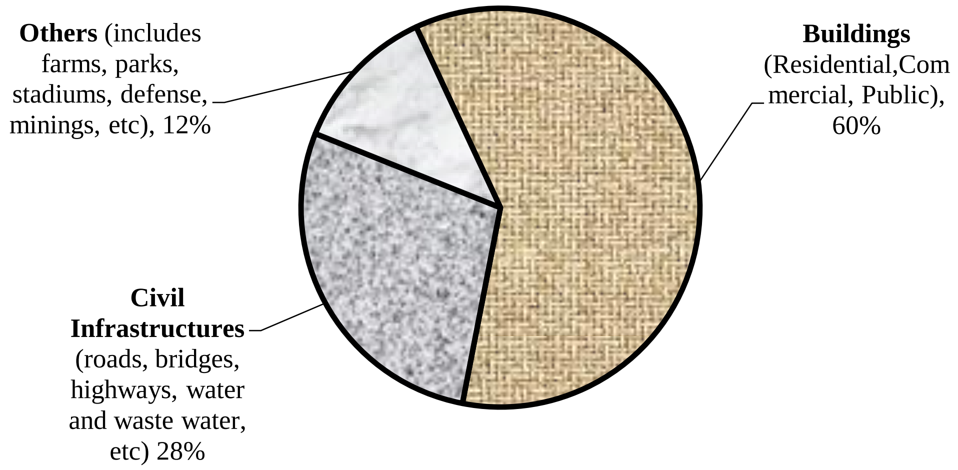


Fig. 5. Recent cement end-use market share in Iran

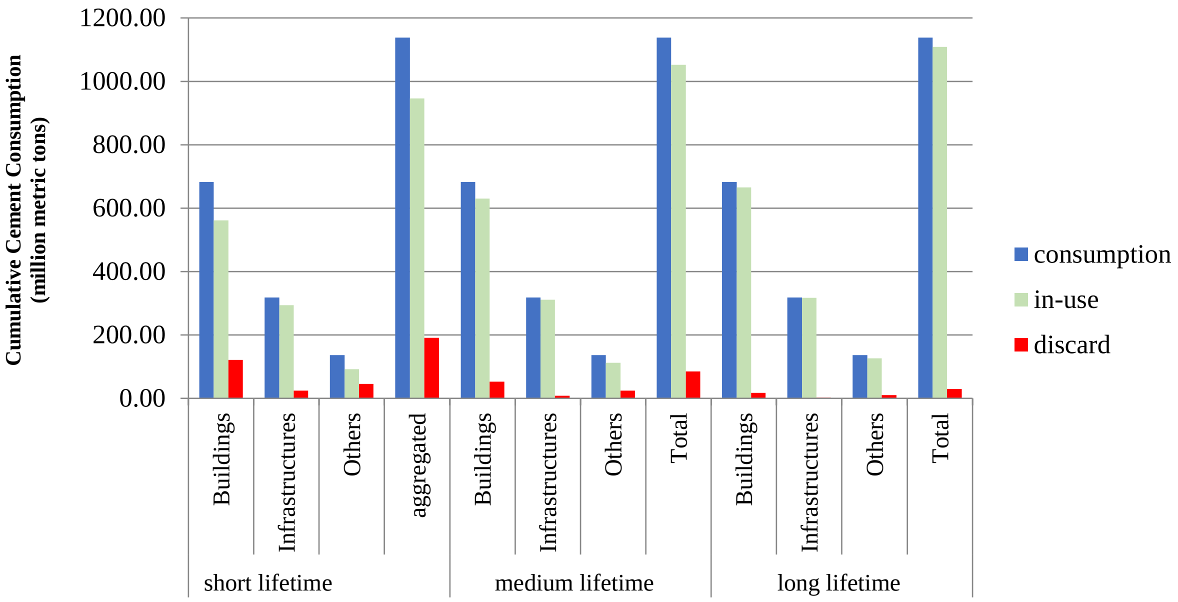


Fig. 6. Cumulative cement consumption, stock of in-use cement and cumulative cement discards at 2018 for different lifetime scenarios (million metric tons)

4.2. Estimate of the Final Stock of in-Use Cement In 2063

Table 4 and Figure 7 show an estimate of the stock of in-use cement in 2063 for different scenarios. As seen in the scenario S3-1, the highest rate of growth in cement consumption and the longest lifetime of cement products (building, infrastructures and others) have led to the largest stock of in-use cement (above 8 Gt) which is almost eight times of stock of in-use cement in 2018. In contrast, in the base scenario S1-3, the lowest rate of growth in cement consumption and the shortest lifetime of cement products have led to the smallest stock of in-use cement (above 2 Gt) which is almost twice the stock of in-use cement in 2018. As seen in Figure 7, the key factor causing larger differences in the final stock of in-use cement is the rate of growth in cement consumption.

Table 4. In-use cement stock (million metric tons) at 2063 for different scenarios

Cement consumption scenarios **Lifetime scenarios**	**High consumption growth (5%)**	**Medium consumption growth (3%)**	**Low consumption growth (1%)**
Sshort lifetime ($\mu_B = 30, \mu_I = 40, \mu_O = 20$)	S 1-1 in-use$_B$ = 4043.22 in-use$_I$ = 2143.50 in-use$_O$ = 655.72 Aggregated = 6842.45	S 1-2 in-use$_B$ = 2227.57 in-use$_I$ = 1239.46 in-use$_O$ = 345.50 Aggregated = 3812.53	S 1-3 (**Base scenario**) in-use$_B$ = 1259.16 in-use$_I$ = 747.54 in-use$_O$ = 185.05 Aggregated = 2191.75
Medium lifetime ($\mu_B = 40, \mu_I = 50, \mu_O = 30$)	S 2-1 in-use$_B$ = 4593.22 in-use$_I$ = 2313.22 in-use$_O$ = 808.64 Aggregated = 7715.09	S 2-2 in-use$_B$ = 2655.98 in-use$_I$ = 1392.54 in-use$_O$ = 445.51 Aggregated = 4494.03	S 2-3 in-use$_B$ = 1601.87 in-use$_I$ = 887.64 in-use$_O$ = 251.83 Aggregated = 2741.35
Long lifetime ($\mu_B = 50, \mu_I = 60, \mu_O = 40$)	S 3-1 in-use $_B$ =4956.90 in-use $_I$ =2427.93 in-use $_O$ =918.64 Aggregated =8303.47	S 3-2 in-use $_B$ =2984.01 in-use $_I$ =1504.29 in-use $_O$ =531.20 Aggregated = 5019.50	S 3-3 in-use $_B$ =1902.09 in-use $_I$ =996.92 in-use $_O$ =320.37 Aggregated = 3219.38

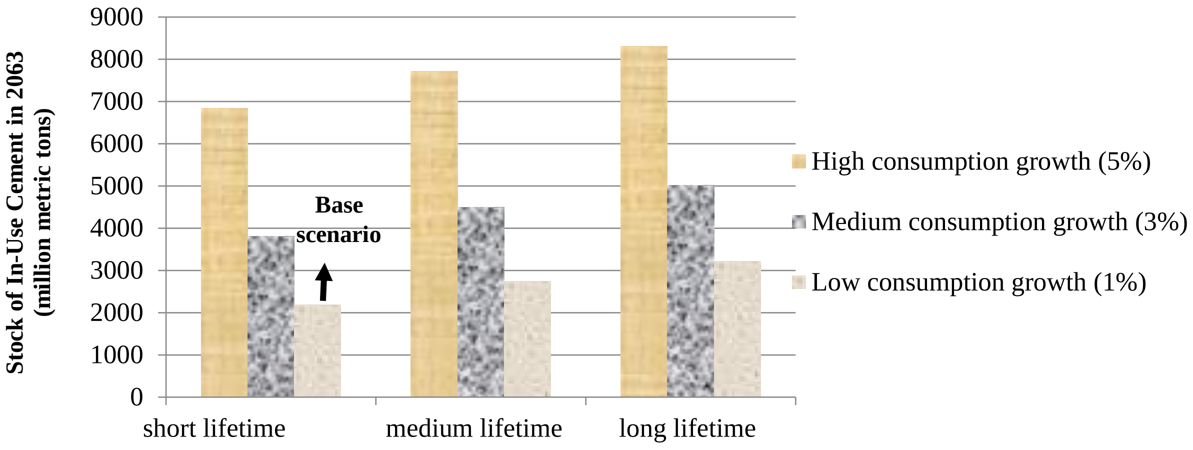


Fig. 7. Thestock of in-use cement in 2063 for different scenarios

4.3. Final Stock of Cement Discards at 2063

Table 5 and Figure 8 show cumulative cement discards until 2063 for different scenarios. (cd denotes cumulative discard). As seen in scenario S1-1, the highest rate of growth in cement consumption and the shortest lifetime of cement products (building, infrastructures and others) have led to the largest stock of aggregated cement discard (above 2 Gt). In contrast, in the scenario S3-3 the lowest rate of growth in cement consumption and the longest lifetime of cement products have led to the smallest stock of aggregated cement discard (less than 1 Gt).

As seen in Figure 8, the amount of cement consumption growth is more affected in the short lifetime scenarios meaning that the key factor influencing the cement discards is the lifetime of structures. This indicates that by increasing the mean lifetime of structures (i.e. building, civil infrastructures and etc.) the amount of cumulative cement discards until 2063 can be drastically decreased and this decrease will not be affected considerably by the consumption growth rate. Furthermore, it is interesting that by averagely making the mean lifetime of the structures one and a half time, the amount of cumulative cement discards until 2063 will be reduced almost to one third (from 2377 in the scenario S1-1 to 879 in the scenario S3-3).

Table 5. Cumulative cement discards (cd) (million metric tons) until 2063 for different scenarios

Cement consumption scenarios **Lifetime scenarios**	**High consumption growth (5%)**	**Medium consumption growth (3%)**	**Low consumption growth (1%)**
Short lifetime ($\mu_B = 30, \mu_I = 40, \mu_O = 20$)	S 1-1 cd_B = 1448.76 cd_I = 438.09 cd_O = 450.68 Aggregated = 2377.52	S 1-2 cd_B = 1300.52 cd_I = 413.65 cd_O = 356.31 Aggregated = 2070.48	S 1-3 (**Base scenario**) cd_B = 1166.47 cd_I = 394.63 cd_O = 295.02 Aggregated = 1856.12
Medium lifetime ($\mu_B = 40, \mu_I = 50, \mu_O = 30$)	S 2-1 cd_B = 938.76 cd_I = 268.37 cd_O = 297.75 Aggregated = 1504.89	S 2-2 cd_B = 886.38 cd_I = 263.95 cd_O = 260.10 Aggregated = 1410.44	S 2-3 cd_B = 845.63 cd_I = 260.27 cd_O = 233.29 Aggregated = 1339.19
Long lifetime ($\mu_B = 50, \mu_I = 60, \mu_O = 40$)	S 3-1 cd_B =575.09 cd_I =153.67 cd_O =187.75 Aggregated = 916.50	S 3-2 cd_B = 565.62 cd_I = 153.21 cd_O = 177.28 Aggregated = 896.11	S 3-3 cd_B = 557.72 cd_I = 152.82 cd_O = 169.13 Aggregated = 879.67

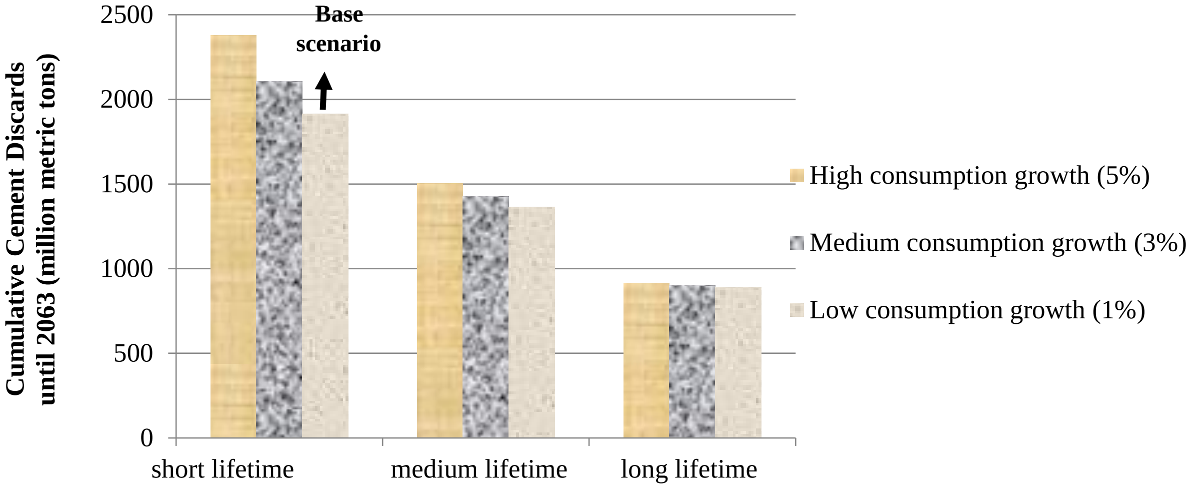


Fig. 8. Aggregated cumulative cement discards until 2063 for different scenarios

Buildings account for the largest portion of cement discards. This is because of the largest share of building in the cement end-use market. Note that in our classification, the category "Buildings" include residential, commercial and public buildings. However, by increasing the average lifetime of buildings it is possible to decrease cement discard from this sector. Cement discards from infrastructures and other end-uses are almost on the same scale.

Note that the model presented in this paper assumes that cement discards exit the economy completely at the end of the product service life. Sometimes this is not an actual assumption because old buildings or structures may be not completely demolished and a part of the structure (such as the foundation) remains in use. In other cases, some abandoned structures and buildings come back into use with an additional service life after appropriate repair and renovations measures. In the field of industrial ecology, the portion of the in-use stock of materials that have been put out of service but not demolished completely is referred to as "hibernating stocks". There is not reliable data or estimate about hibernating stock of cement in Iran and it cannot be determined with the presented model. It is necessary to perform empirical research in this regard to estimate the size of hibernating stocks. If hibernating stocks can be estimated, then those estimates should be subtracted from the estimated discard of this study to drive the true cement discards.

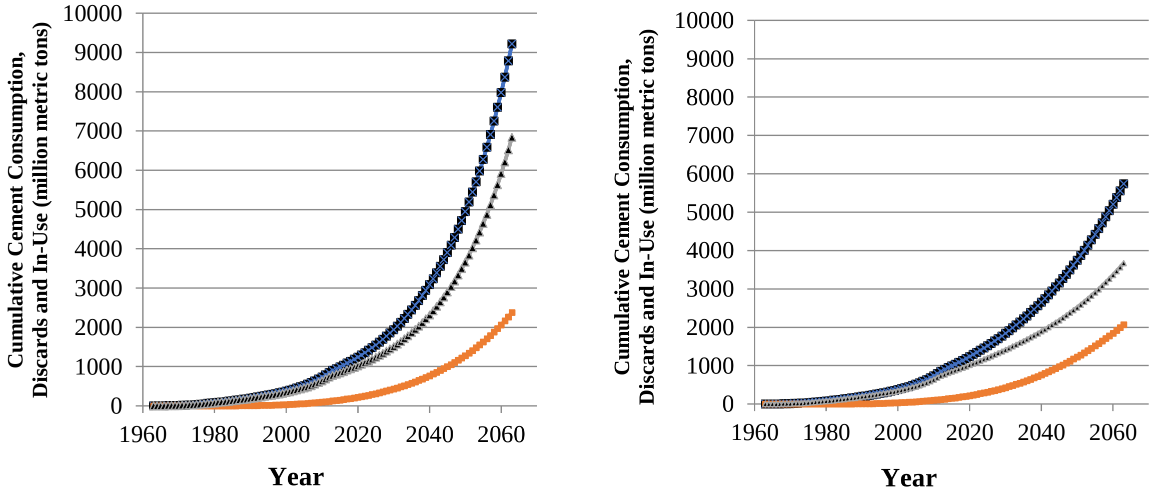
4.4. Past and Future Trends of Cumulative Aggregated Cement Consumption, Discards and in-Use

Cumulative aggregated cement consumption, discards and in-use for all scenarios are depicted in Figure 9. In scenarios with the short lifetime (S1-1, S1-2, S1-3) the model derived estimate of in-use cement stock for the year 2019 is 982 Mt (near 1Gt). This indicates that 83% of the cement utilized during the last half-century is still in use. For scenario S1-1, an estimate of in-use cement stock for 2063 is 6842 Mt. This is almost 7 times of in-use stock in 2018 and indicates that 74% of the cement utilized during the period 1963-2063 will be in use in 2063. However, for scenarios S1-2 and S1-3, an estimate of in-use cement stock for 2063 is 3670 and 2031 Mt respectively. Thus the portions of in-use cement from total cement consumption in 2063 for these scenarios are 64% and 52% respectively.

To understand the effect of structures lifetime on the stock of in-use cement it is helpful to compare the results from scenario S1-1 with S3-1. In both scenarios the growth rate of cement consumption is 5% but the mean lifetime of structures at scenario S3-1 is almost one and a half time of the corresponding lifetime in scenario S1-1. The result is that the portion of in-use cement from total cement consumption in 2063 for S3-1 is 90%. Comparing this value with 74% for scenario S1-1, it is found that by increasing the mean lifetime of the structures, a larger fraction of total cement consumption will be in use and in other words, a smaller fraction of total cement consumption will be discarded.

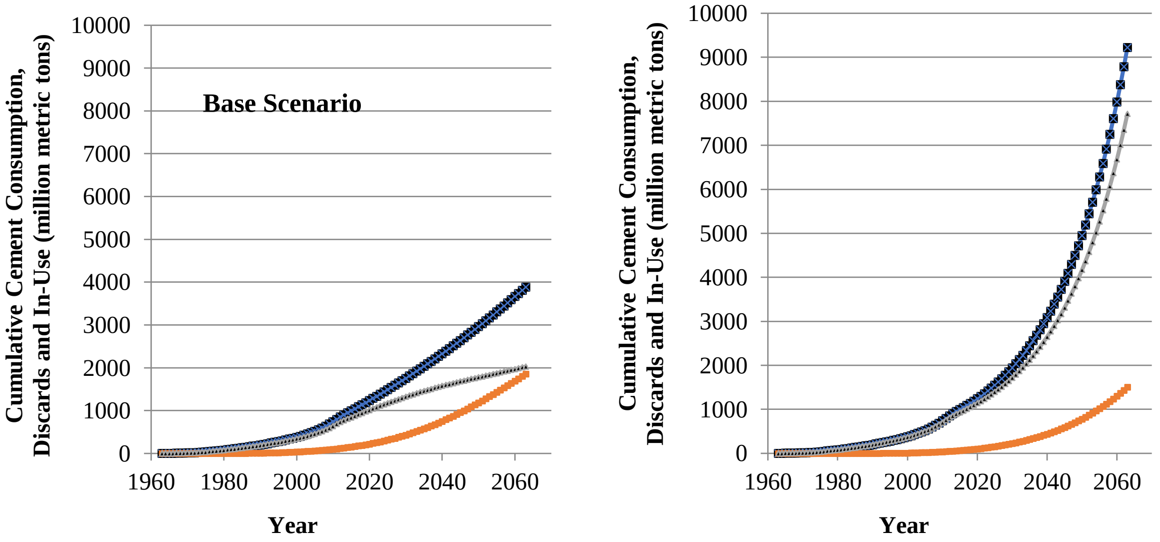
4.5. Past and Future Trends of Annual Cement Consumption and Discards

Figure 10 shows cement consumption and discards (aggregated and sectoral) in each year for all scenarios. It is worth noting that to provide more resolution in charts of Figure 10 their vertical axes are depicted in different scales. As seen in the scenario S1-1, the annual aggregated cement discard in 2063 is above 100 Mt. From an environmental point of view this is the worst case. The portion of buildings from this stock of cement discard is over 60%. The great value of annual cement discard in this scenario originated from the bigger rate of cement consumption growth and the lower lifetime of structures in contrast with other scenarios. However, by decreasing the cement consumption growth rate and increasing the average lifetime of structures, annual cement discard will be reduced considerably. From an environmental point of view, the scenario S3-3 is the best where the annual cement discard in 2063 is slightly above 40 Mt. This addressed a reduction of near 60% comparing with the corresponding value in the scenario S1-1.



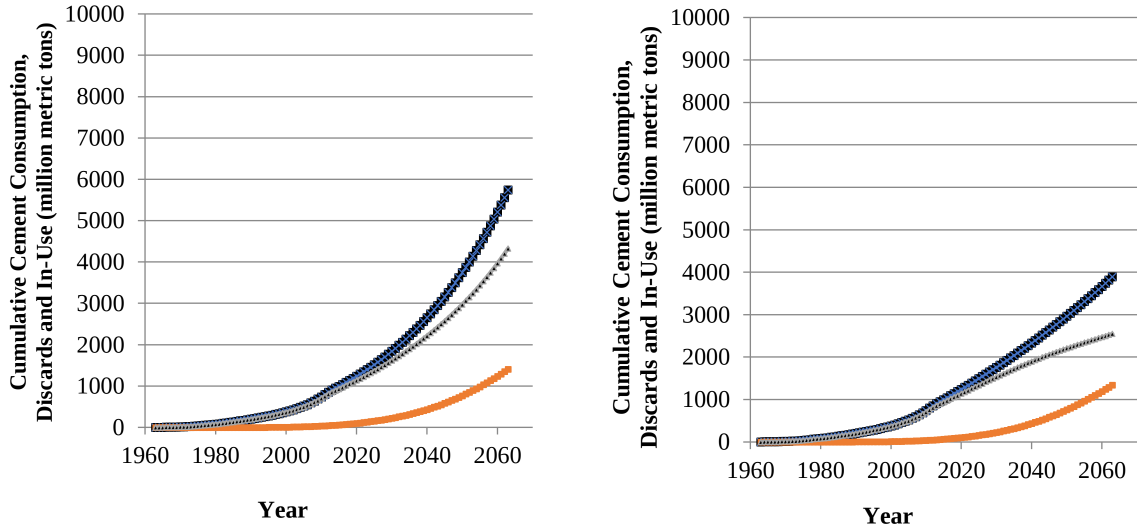
Scenario S 1-1

Scenario S 1-2



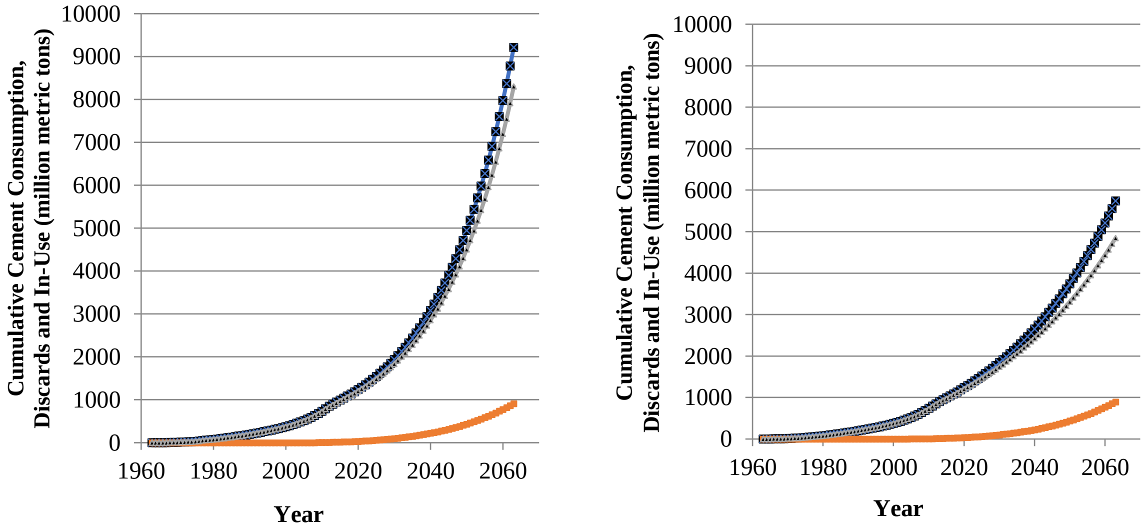
Scenario S 1-3

Scenario S 2-1



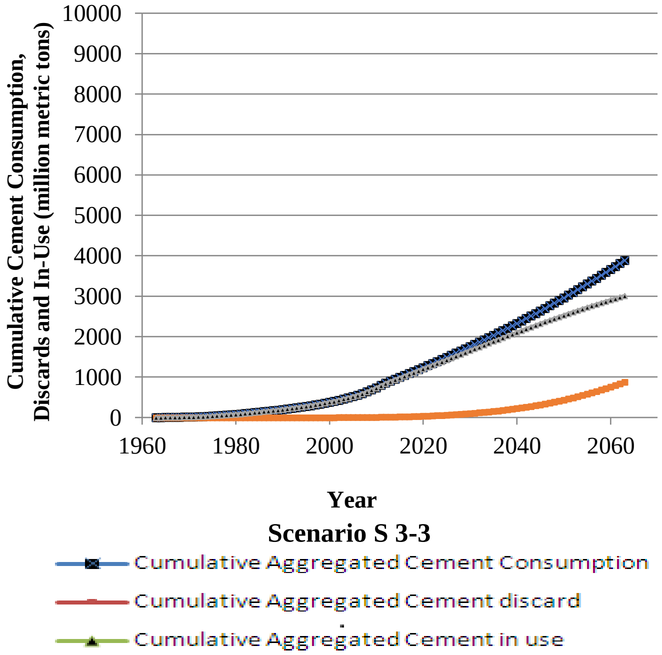
Scenario S 2-2

Scenario S 2-3



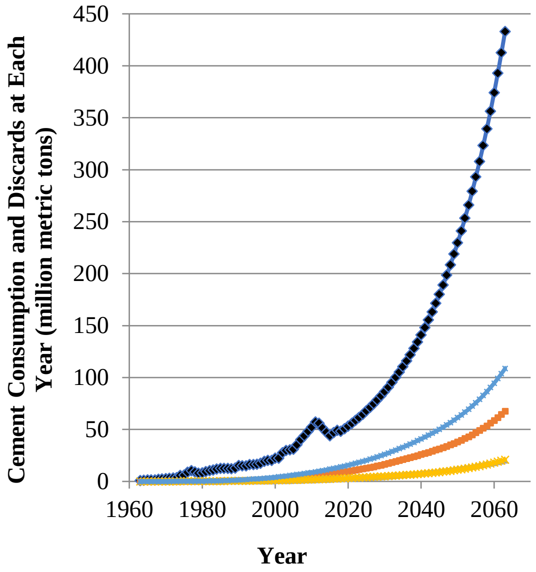
Scenario S 3-1

Scenario S 3-2

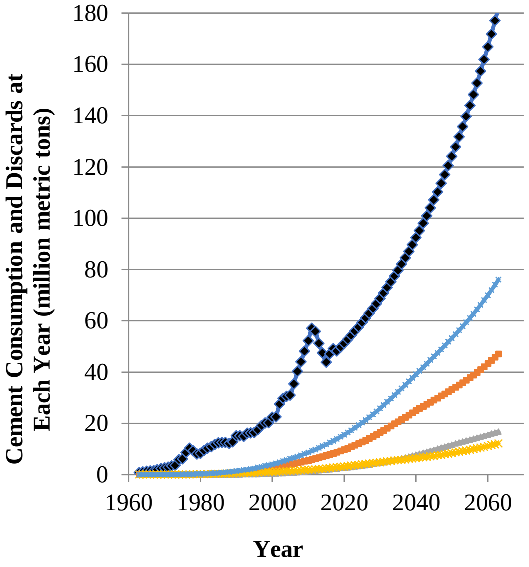


Scenario S 3-3

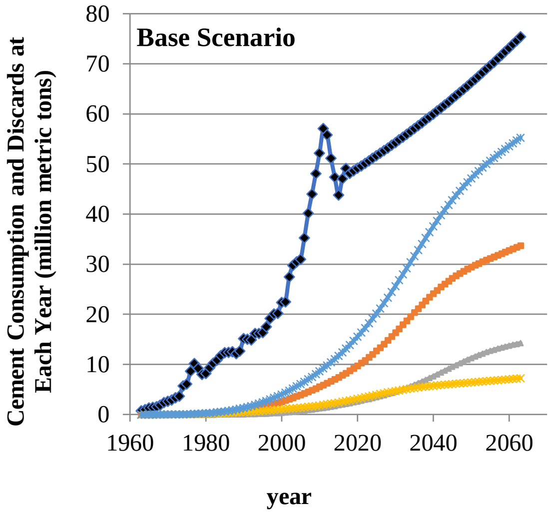
Fig. 9. Cumulative aggregated cement consumption, discards and in-use for all scenarios



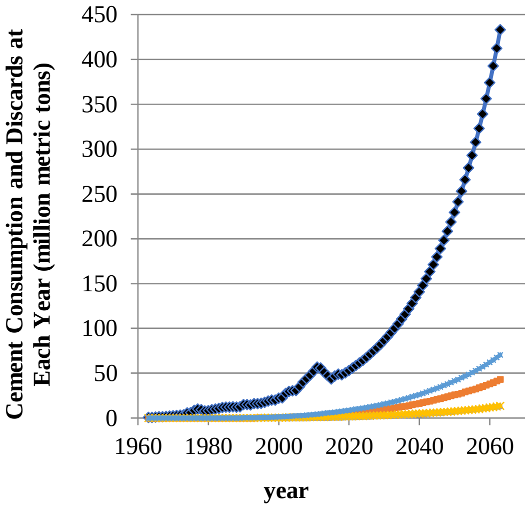
Scenario S 1-1



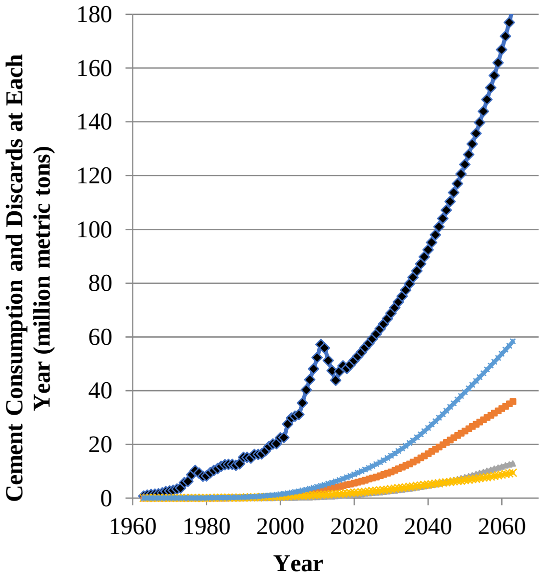
Scenario S 1-2



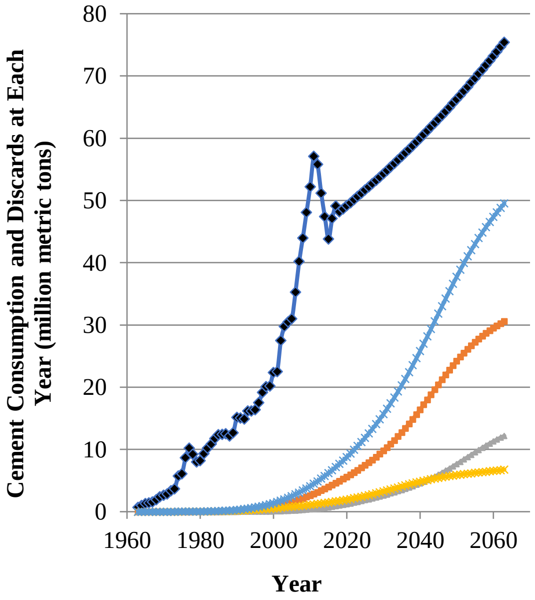
Scenario S 1-3



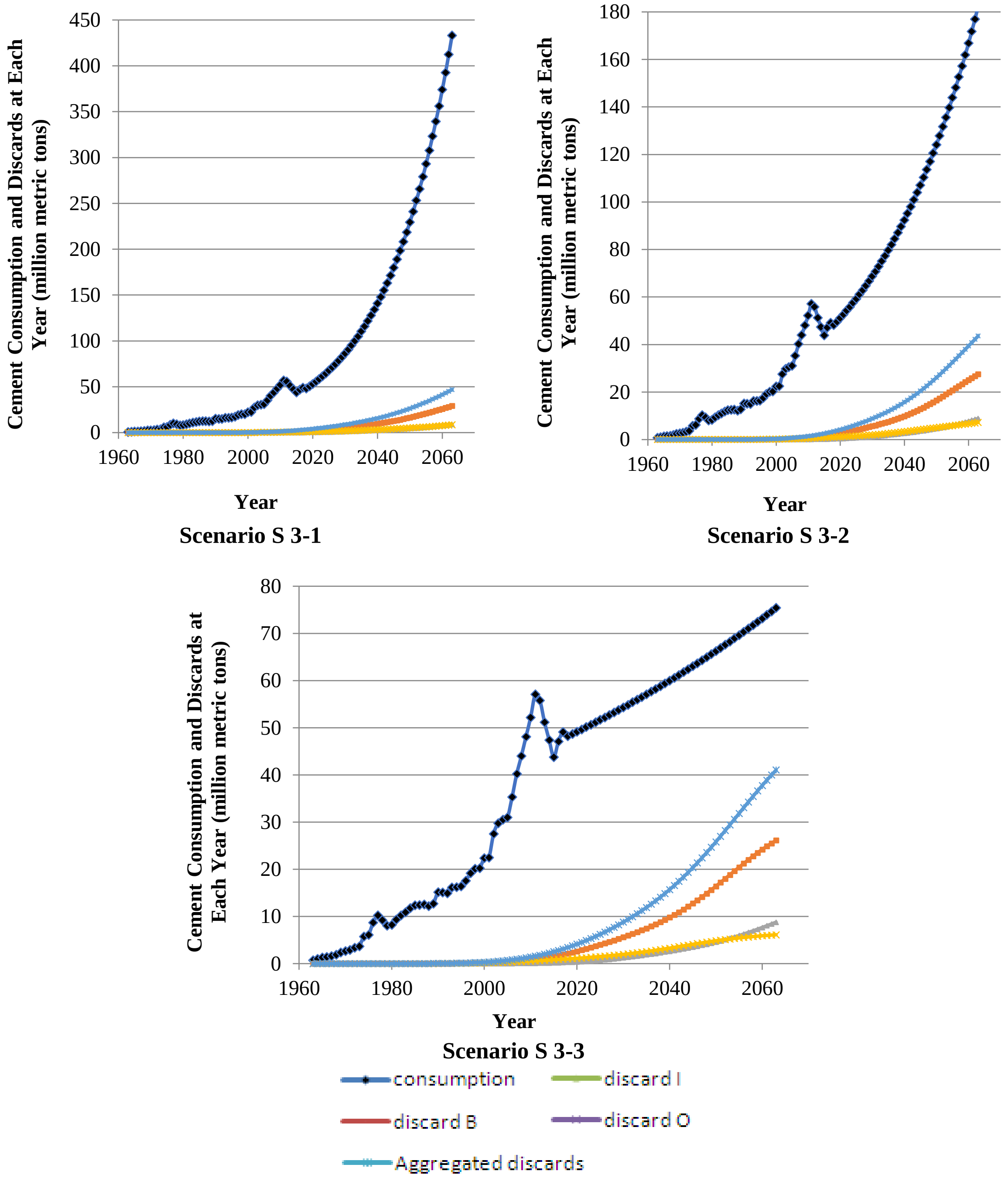
Scenario S 2-1



Scenario S 2-2



Scenario S 2-3



Scenario S 3-1

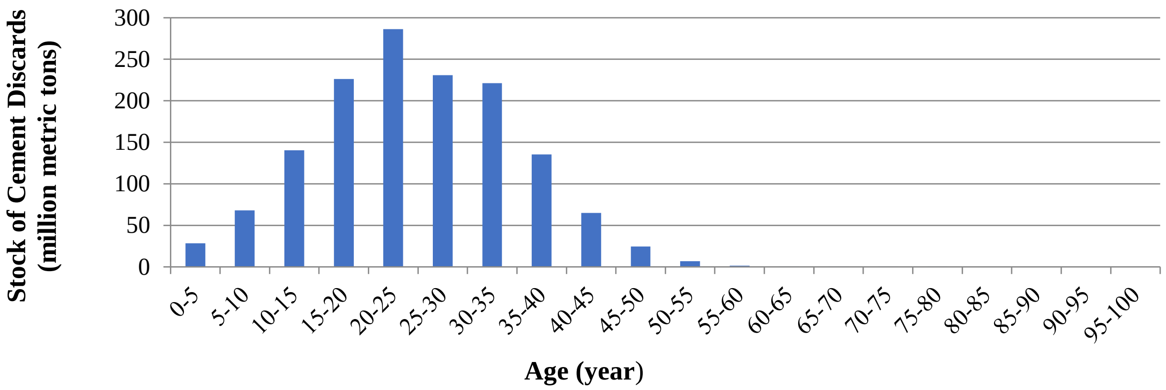
Scenario S 3-2

Scenario S 3-3

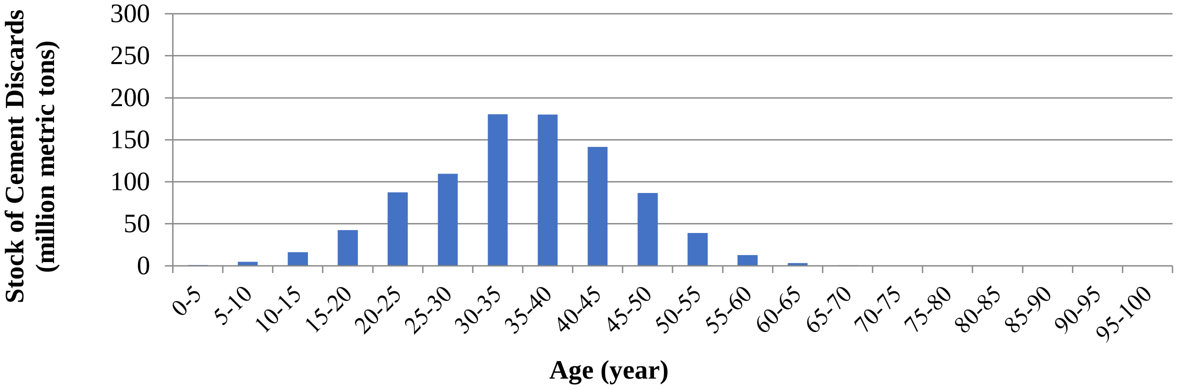
Fig. 10. Cement consumption and discards (aggregated and sectoral) at each year for all scenarios

4.6. Age Distribution of the Cement Discards for the Building Sector

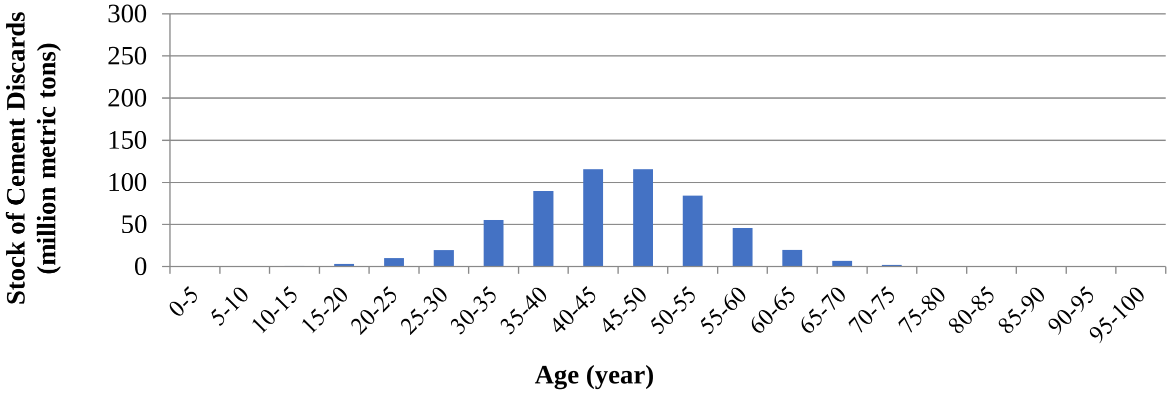
Age distributions of cement discards for the building sector are demonstrated in Figure 11. In this context "age" means the time delay between entering a stock of cement into use and discarding it from usage. Three scenarios are selected for comparison. The normal distribution of the lifetime of buildings is graphically seen as assumed in the model formulation. Different average lifetimes of these scenarios are seen in these charts. In scenario S1-1, the biggest stock of cement discard that belongs to age category 20-25 years is 286 Mt. The biggest stock of cement discard in scenario S2-1 (belonging to the age category 35-40) is 180 Mt and the biggest stock of cement discard in scenario S3-1 (belonging to the age category 45-50) is 115 Mt. These findings indicate that longer lifetime of buildings results in smaller stock of cement discard in the time horizon of this study.



Scenario S 1-1 (Short lifetime, $\mu_B = 30$)



Scenario S 2-1 (Medium lifetime, $\mu_B = 40$)

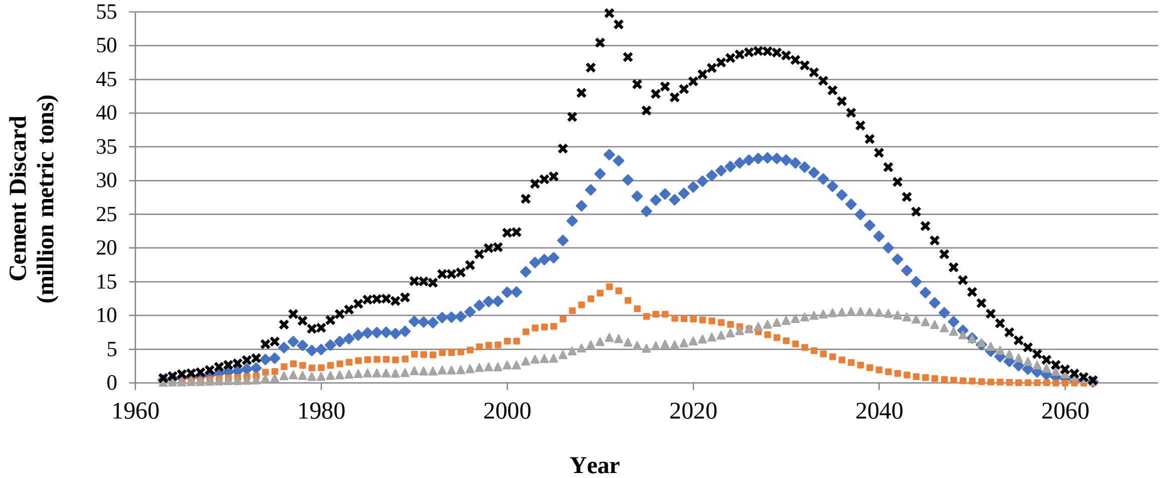


Scenario S 3-1 (Long lifetime, $\mu_B = 50$)

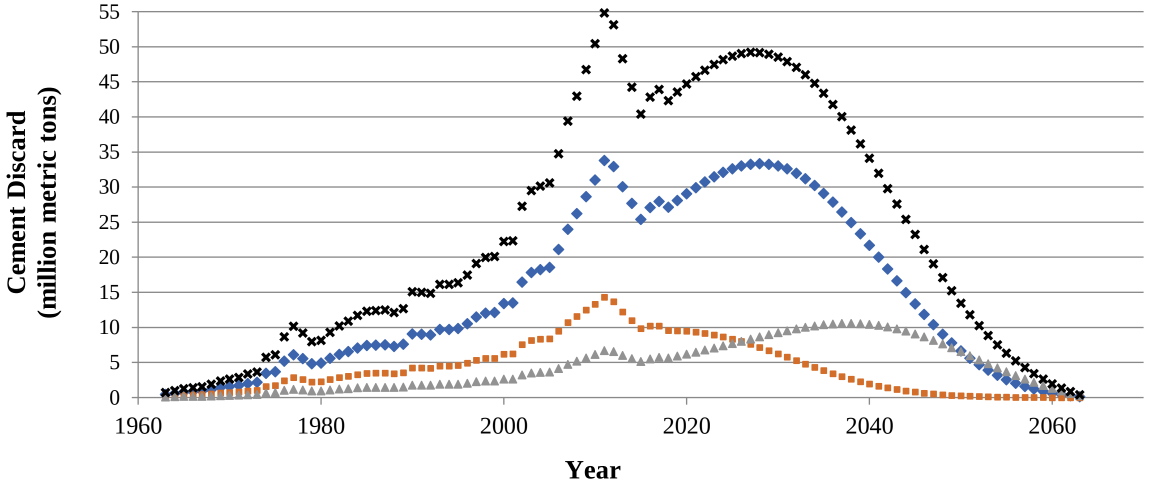
Fig. 11. Age distribution of cement discards for building sector

4.7. Other Results

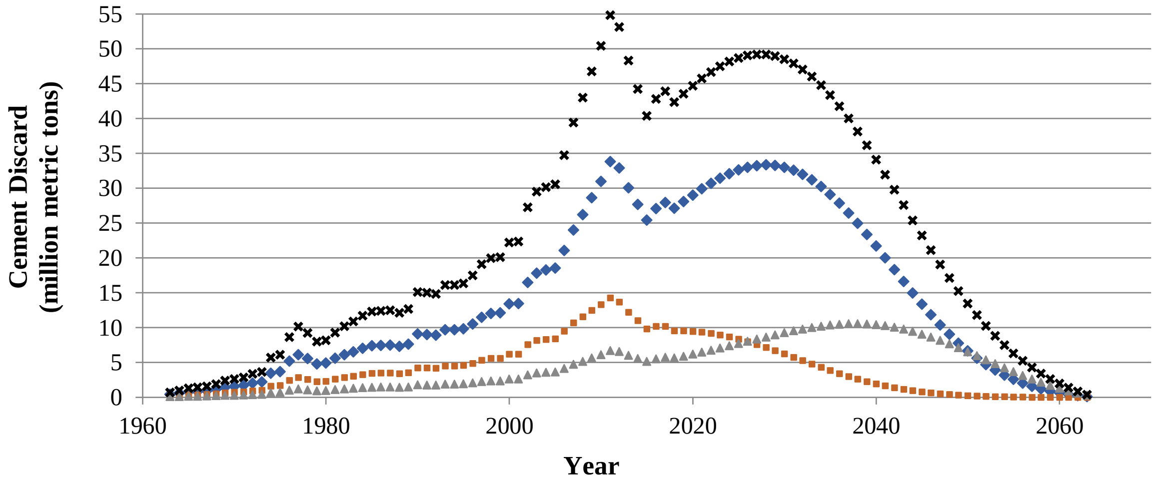
Total cement discards originating from cement consumption at year t is presented in Figure 12. Three scenarios are selected for comparison. In the scenario S1-1 there are two peaks in the aggregated discard curve; one in 2010 and the other in 2030; meaning that the largest stock of cement discard originates from cement consumed at these times. But at scenarios S2-1 and S3-1 aggregated discard curve has one peak in 2010. The cause of second peak (i.e. 2030) in scenario S1-1 is the shortness of structures lifetime. In this scenario, the average of mean lifetimes among three sectors of cement end-uses is 30 years and a large portion of cement consumed at 2030 will be discarded until 2063 (i.e. the end of the time horizon of the study). But in scenarios S2-1 and S3-1, the average of mean lifetimes is 40 and 50 years respectively and a major portion of cement consumed in 2030 will be discarded after 2063 and hence has been excluded from this study. It is notable that the cause of not seeing any peak before 2010 is the value of annual cement consumption in this interval that is lower than consumption in 2010. Briefly the stock of cement consumed in 2010 is large enough and has enough time to be discarded until 2063 (in all scenarios) so formed a peak in all three curves in Figure 12.



Scenario S 1-1 (Short lifetime)



Scenario S 2-1 (Medium lifetime)



Scenario S 3-1 (Long lifetime)

Fig. 12. Cement discard originating from cement consumption at each year

4.8. Strategic Recommendations for the Sustainability of Buildings and Civil Infrastructures

4.8.1. Prolonging the Lifetime of Buildings and Infrastructures to Increase the Longevity of in-Use Cement Stock and Reduce Cement Demand and Cement Waste

Findings in previous sections have some clear implications and advice for different stakeholders of cement industries in Iran. The building sector has the largest portion of the cement end-use market in Iran. However, buildings in Iran have a lower average lifetime in contrast with global norms (RHUDRC, 2019). As findings show, by increasing the mean lifetime of the buildings, the amount of cumulative cement discards until 2063 in this sector can drastically be decreased from 1167 Mt in the base scenario to 557 Mt in scenario 3-3. In scenario 3-1 (with high cement consumption growth rate) cumulative cement discards until 2063 is 575 Mt. This show that the decrease in cumulative cement discards will not be affected considerably by the cement consumption growth rate in the future. Thus designing and implementing initiatives to increase the mean lifetime of the buildings is a reliable strategy to decrease cement discards in the long term future.

From an environmental point of view performing initiatives to increase the mean lifetime of structures (especially buildings) is a valuable act. The cement industry is an energy-intensive industry and accounts for 15 % of industrial energy consumption and 4% of total energy consumption in Iran (Alihosseini et al., 2009). Furthermore, the cement industry is a pollutant one and emits one million tons of CO_2 to produce one million tons of cement. According to third Iranian communication to the United Nations framework convention on climate change (UNFCCC), with the production of about 34,432 Gg of CO_2, the cement industry is responsible for about half of process-based CO_2 emission in Iran (Department of Environment, 2017).

By increasing the mean lifetime of the structures, a smaller fraction of total cement consumption will be discarded. Thus there would be a lower need for new cement production (at least for domestic consumption) and this decrease energy consumption and CO_2 emission in cement industries. The direct benefit of a decrease in cement discard is that a lower amount of disposed material will be accumulated in the environment. This is more important because the recycling process of construction material including cement and concrete is not well developed still in Iran. These findings are in agreement with the research done by Miller (2020) in the USA. Miller showed that if cement longevity could increase by 50%, material resource demand and GHG emissions from concrete production will reduce 14% in the United States.

Findings in section 4.7 show that if the lifetime of the buildings and infrastructures can be almost doubled, the rise of the second waste peak will be pushed to the next half of the century. Therefore, for mid-term waste reduction, the most important strategy is to prolong the lifetime of the buildings and infrastructures. The first way is to ensure a greater service life for the new construction through the improvement of construction techniques and better urban planning. The second way is to enhance the existing building stock management by, for instance, regular renovation and rehabilitation.

4.8.2. Enhancing the Recycling of Concrete to Reduce Disposed Cement in the Environment

The dynamic MFA for the cement in the Iranian economy establishes a base to understand the mechanism of future generation of cement waste in Iran and the potential of various waste management strategies. It indicates that cement waste generation in the future strongly depends on the lifetime of the buildings and infrastructures. Therefore, as a mid-term strategy, the main focus should be on prolonging the service life of the buildings whenever it is possible. However, all the scenarios demonstrate that the dramatic rise of cement waste generation will arrive sooner or later (note that cumulative cement discard at 2063 for different scenarios ranges from 879 Mt to 2377 Mt). Because this large amount of cement waste is unavoidable, concrete recycling should be emphasized to restrict the pressure on landfills and reduce impacts on the environment. Thus, it seems a suitable long-term strategy for Iran to increase concrete recycling capability and invest in enhancing concrete recycling technology, promoting high recyclability design, and so on. This is the main strategy to prevent the city's landfill capacity being used up completely by huge amounts of demolition waste. Suggestion for improving the recyclability of cement-based product has been provided in many studies in the context of construction and demolition (C&D) waste management such as Kapur et al. (2008), Hu et al. (2010b), Bergsdal et al. (2007b) and Huang et al. (2013).

4.8.3. Controlling the Growth of Cement Consumption in the Construction Industry

It is clear that prolonging the average lifetime of the in-use cement stock and reducing the cement intensity of buildings and infrastructures would be the top priority policies to reduce cement consumption in the foreseen future. Using supplementary cementitious materials (SCMs) is a way to reduce cement intensity that is attracting attention in the global research community. Askarinejad (2017) proposed three different methods of nanofabrication, using ultrasound irradiation, solvothermal /hydrothermal process and microwave irradiation, that were used for activation of two types of SCMs. Optimizing the use of cement by adoption of material efficiency strategies, would led to reduce demand throughout the entire construction value chain, helping to cut CO_2 emissions from cement production. Lower cement demand can be achieved through actions such as optimizing the use of cement in concrete mixes, using concrete more efficiently, minimizing waste in construction, and maximizing the design life of buildings and infrastructure (RHUDRC, 2019).

There are several additional means to benefit concrete buildings and infrastructure through increasing material efficiency. Improving yield loss during concrete manufacture, where possible, and reducing over-ordering of material for construction projects also can be considered as material efficiency improvement measures that could help in environmental impact mitigation. In current practice in Iran, 340 kg of cement are used to produce one cubic meter of concrete. The compressive strength of the resulting concrete is less than 25 MP. It is far from the planned 50 MP compressive strength for concrete (RHUDRC, 2019). Engineering concrete in such way to provide necessary properties with less material can reduce material flows associated with the concrete as well as structural systems needed to support the concrete. Eghbali et al. (2019) performed a study on the problem of material loss/construction waste in the Iranian building industry considering the impact of critical shortcomings in the stages of design, construction and supervision as the main phases of construction process. They concluded that construction project managers, engineers, contractors and workers in Iran believe that from 40 to 100 percent of construction wastes can be reduced using prefab construction methods. So, prefabrication would be considered as a solution to waste reduction in the Iranian building industry.

5. Conclusions

To the best of our knowledge, it is the first time a research was conducted to simulate the dynamic material flow of cement in Iran. The model developed in this research was a flow dynamic one and had a retrospective and prospective approach. It was an open-loop model and ignored capacity constraints of the production and different scenarios of end of life. Like many other studies in this area a normal lifetime distribution was adopted for all structures. Different scenarios for the mean lifetime of structures and cement consumption growth were designed and simulated. Results showed a considerable and reliable impact of prolonging the lifetime of structures (especially buildings) on decreasing future cement discards. Furthermore, for long-term strategies, suggestions for enhancing the recycling of concrete to reduce disposed cement in the environment were offered. Controlling the growth of cement consumption in the construction industry by reducing cement intensity of buildings and infrastructures and minimizing construction waste are also recommended.

For future studies it is recommended to add a production-export sub-model with parameters such as export growth rate and production growth rate to assess the effect of cement production capacity, which is under installation in the near future. Considering recycling in the model aid to partition the estimated total discards into the landfill and recycling reservoirs and makes the model more realistic. Another direction for future research is incorporating other lifetime distribution functions such as Weibull and gamma in the model and investigating their effects on the results. Considering emissions such as CO_2 and other environmental impacts in the model provide a platform to assess the environmental effects of cement production, consumption and discards for the future. Finally, an important suggestion for the future researches may be expressed as developing a stock dynamic model in which the stock of service units is the driver for the material inflows.

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