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Time-varying losses in material flows of steel using dynamic material flow models

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ABSTRACT

A method for annual evaluation of recycling rates in material flows was established to enable a consistent analysis of resource utilizations. The algorithm to calculate the time-varying losses was derived based on a sound statistical approach that would be viable for both historical data and future predictions. This method eliminates the need for adjustable parameters and is solely based on input data of the material consumption and scrap collection. This article describes the model methodology and the calculation procedures to classify the societal scrap reserve from the amounts of losses, based on statistics. These statistical models contribute to establish a standardized method to obtain consistent results. Based on the method the lifetime of steel data was for the first time calculated on an annual basis for the steel usage as well as for the end of life scrap amount. This was done for the Swedish steel consumption and the global steel consumption between 1900 and 2013 as well as for future predictions between 2013 and 2060. The lifetime of steel was calculated to be higher in an industrialized country such as Sweden compared to the global average value. More specifically, the service lifetimes of EOL steel in Sweden and in the World were calculated to be 35 and 28 years in 2012, respectively. This novel approach of using system specific data on the lifetime of steel on an annual basis enables a possibility to evaluate recycling trends and potentials to increase the recycling rate.

1. Introduction

Dynamic material flow models (DMFM) are used as tools to evaluate the long-term trend with respect to the material use and the material stock dynamics. These analysis are of importance to evaluate the environmental footprint of materials as well as to evaluate the potential of increasing recycling in society. DMFMs can be used to calculate parameters such as recycling rates, in-use metal stocks, societal scrap reserves and amounts of losses. In addition, to forecast the demand of metals to industrialize countries as well as to evaluate resource limitations associated with an industrialization. These analysis are of importance for society to preserve natural resources and to decrease the degradation of landscapes. Moreover, to evaluate the potential of reducing the energy usage and greenhouse gas emissions associated with the industry. This can be done by utilizing metal scrap and implementing energy efficiency in the future.

Dynamic material flow models are based on the concept of evaluating the inflow and outflow of materials in combination with using lifetime analysis. Previous DMFMs are based on input parameters such as the lifetime of steel data, minimum and maximum lifetimes, lifetime distribution functions, in-use metal stocks and yield rates etc. (STAN, 2016; Cencic and Rechberger, 2008; van Schaik and Reuter, 2004; Davis et al., 2007; Igarashi et al., 2007, 2005; Fenton, 1998; Melo, 1999; Mueller et al., 2011, 2007; Gyllenram et al., 2012; Pauliuk et al., 2013; Hatayama et al., 2010; Daigo et al., 2007, 2010, 2015; Xuan and Yue, 2016; Park et al., 2011). All previous DMFMs have used sector-specific single value data on the lifetime of steel, obtained from measurements on products and applications in society, as the basis of the models (van Schaik and Reuter, 2004; Davis et al., 2007; Igarashi et al., 2007, 2005; Fenton, 1998; Melo, 1999; Mueller et al., 2011, 2007; Gyllenram et al., 2012; Pauliuk et al., 2013; Hatayama et al., 2010; Daigo et al., 2007, 2010, 2015; Xuan and Yue, 2016; Park et al., 2011). For the lifetime measurements, it has not been possible to distinguish the service lifetimes of steel from the time period the end-of-life products have been redundant. In DMFM, this has further made it difficult to distinguish the amounts of losses from the amount of societal scrap reserve available for future collection in society. Based on the lifetime measurements, it has been difficult to obtain consistent data on the lifetime of materials on an annual basis. This due to lack of extensive data on lifetime measurements

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Nomenclatures

Steel consumption Finished steel products production in society corrected for the export and import of the same product groups.
Scrap collection Purchased domestic old and prompt steel scrap adjusted for export and import of steel scrap.
Societal steel scrap reserve The end-of-life steel containing products and applications that is available for collection.
Redundant The stage when products and applications reaches its end-of-life phase and are no longer in-use for its application purpose.
Losses The societal steel scrap reserve that has been redundant for more than a lifetime of steel and that is not recoverable due to statistics. Specifically, the losses can be interpreted as the redundant steel that is not economically feasible to collect for recycling purposes.
Viable steel scrap The economically feasible amount of steel scrap available for collection including the scrap stock at the waste management companies and collection systems in society. The viable steel scrap is a part of the societal steel scrap reserve.
Workable losses The amounts of losses that potentially could be recycled in the future based on new technology. The workable losses are the reversible amounts of losses and are included in the total amounts of losses in society.
In-use steel stock The total amount of steel consumed in countries to build up the infrastructure and the steel consumed in products and applications. The in-use steel stock is the functional amount of steel that is used for its application purpose.
Recycling rate (RR) The ratio of the scrap collection divided by the sum of the amounts of losses and scrap collection (RR). 100% minus the RR value corresponds to the ratio of the losses.
Recycling rate of the theoretical scrap (RR-TS) The ratio of the scrap collection divided by the sum of the losses, societal steel scrap reserve and scrap collection (RR-TS). 100% minus the RR-TS value corresponds to the ratio of the societal steel scrap reserve and amounts of losses.
Full lifetime The time duration between the steel consumption and scrap collection. The service lifetime of steel and the time period the steel is redundant.
True lifetime The time duration between the steel consumption subtracting the societal steel scrap reserve and the collected scrap. The service lifetime of steel.
Theoretical scrap generation (TSG) The sum of the societal steel scrap reserve, amounts of losses and collected scrap.
Potential scrap generation (PSG) The sum of the societal steel scrap reserve and collected scrap.
Workable scrap generation (WSG) The sum of the viable steel scrap, amounts of workable losses and collected scrap.
Viable scrap generation (VSG) The sum of the viable steel scrap and collected scrap.

List of symbols (Greek)

$\varepsilon_t^{(1)}$ Recycling rate of the potential steel scrap generation (collected scrap/(Societal steel scrap reserve + collected scrap))
$\varepsilon_t^{(2)}$ Recycling rate of the theoretical scrap generation (collected scrap/(Societal steel scrap reserve + Losses + collected scrap))
$\varepsilon_t^{(3)}$ Recycling rate of steel (collected scrap/(Losses + collected scrap))
$\bar{\varepsilon}_t^{(1)}$ Recovery rate of the viable steel scrap generation (collected scrap/(viable stock + collected scrap))
$\bar{\varepsilon}_t^{(2)}$ Recovery rate of the theoretical scrap generation (collected scrap/(viable stock + workable losses + collected scrap))
$\bar{\varepsilon}_t^{(3)}$ Recovery rate of the workable steel scrap (collected scrap/(workable losses + collected scrap))
$\lambda_t^{(1)}$ Full lifetime of end of life steel
$\lambda_t^{(2)}$ True lifetime of end of life steel
$\bar{\lambda}_t^{(1)}$ Full lifetime of steel usage
$\bar{\lambda}_t^{(2)}$ True lifetime of steel usage
ω_t Societal steel scrap reserve
γ_t Losses of steel
θ_t In-use steel stock per capita
$\bar{\omega}_t$ Viable steel scrap
$\bar{\gamma}_t$ Workable losses
$\bar{\theta}_t$ Upper limit of the in-use steel stock per capita

Latin

DMFM Dynamic material flow model
EOL End of life
m_t^f Steel scrap collection
$m_t^{(\bar{g})}$ The effective maximum steel consumption
$m_t^{(g)}$ The effective steel consumption
m_t^h The steel consumption
$t^{(0)}$ Starting year
$t^{(1)}$ Time to consume the steel scrap for a given year
$t^{(2)}$ Time to collect the same amount of steel consumption as collected steel scrap
$t^{(3)}$ Time to collect the same amount of steel scrap as consumed effective steel consumption
$\bar{t}^{(1)}$ Time to consume the steel consumption for a given year
$\bar{t}^{(2)}$ Time to collect the same amount of steel scrap as consumed steel
$\bar{t}^{(3)}$ Time to collect the same amount of steel scrap as consumed effective maximum steel consumption

Function

h_t The steel consumption in society
f_t The steel scrap collection in society
g_t The effective steel consumption
$\bar{g}_t$ The effective maximum steel consumption