Using Dynamic Stock & Flow Models for Global and Regional Material and Substance Flow Analysis in the Field of Industrial Ecology

The Example of a Global Copper Flow Model

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Introduction: Industrial Ecology and Material Flow Analysis (MFA)

Influenced by the natural ecosystem the Industrial Ecology approach provides an integral view on material flows used in industrial processes. Its goal is to use the waste of one process as input material for other processes, thereby minimizing losses to the environment.
An important tool of Industrial Ecology is the Substance Flow Analysis (SFA), a special form of the more broadly defined Material Flow Analysis (MFA). Carrying out a SFA allows us to track each tonne of a specific material, for example metals, on its way through different life stages, starting with mining operations, followed by product fabrication and usage, and finally the discard or recycling of waste.

Material cycles	global	regional	national	total
static	47	105	791	943
dynamic	9	7	60	76
total	56	112	851	1019

Table 1 Analyses carried out by previous studies show a significant underrepresentation of dynamic approaches (Chen, Graedel 2012). Thus, there is a great potential for the usage of dynamic stock and flow modeling in the field of Industrial Ecology as it is provided by System Dynamics.

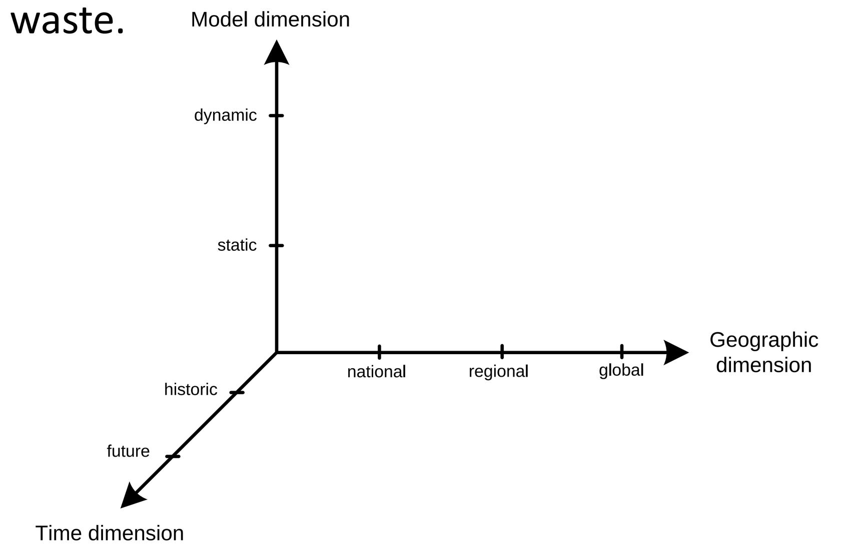

Figure 2 Proposed categorization of raw material cycles according to their used methodology, geographical focus and time coverage.

Methodology: Delay Functions & Equations of Mass Balance

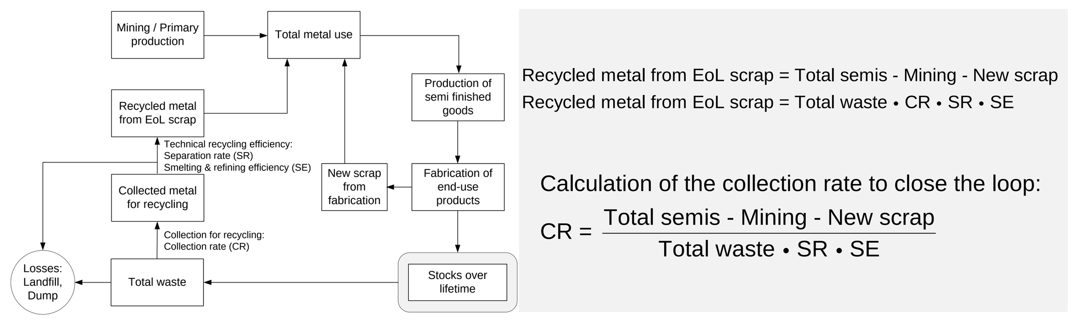

Figure 3 Simplified methodology to enable a closed mass balance by calculating the EoL Collection Rate as a function of production data. By applying this method, the conservation of mass is enabled at every time step and the consistency of the simulated data is guaranteed.

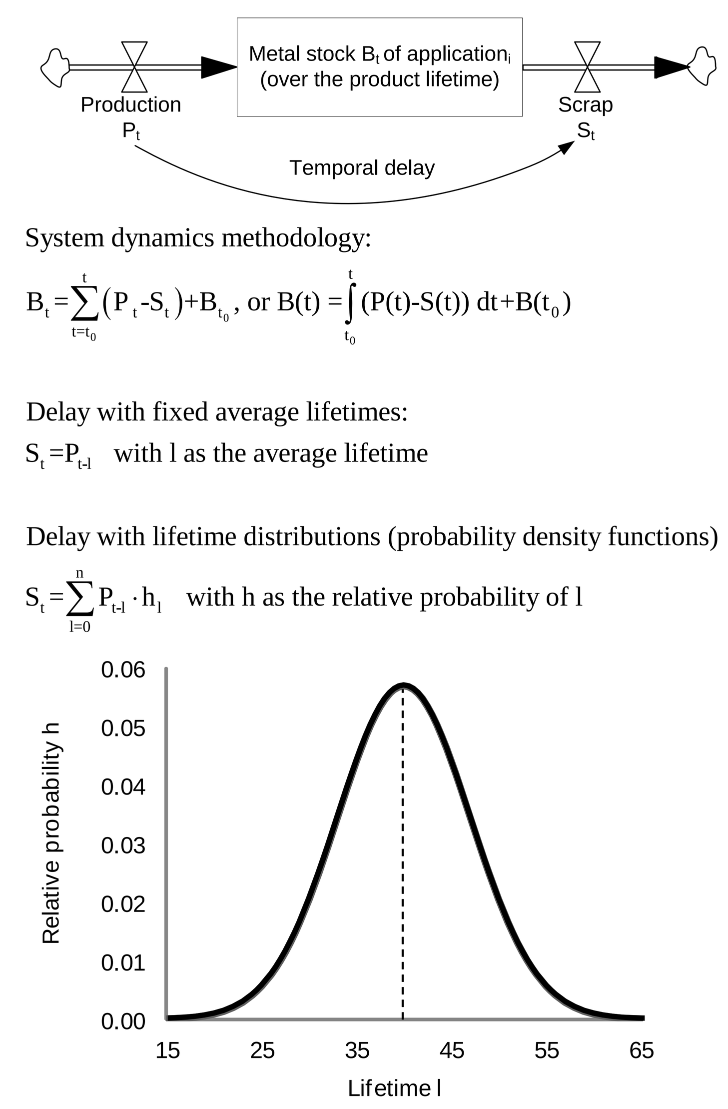

Figure 4 Basic methodology to estimate metal stocks in use and waste flows by using different forms of temporal delays

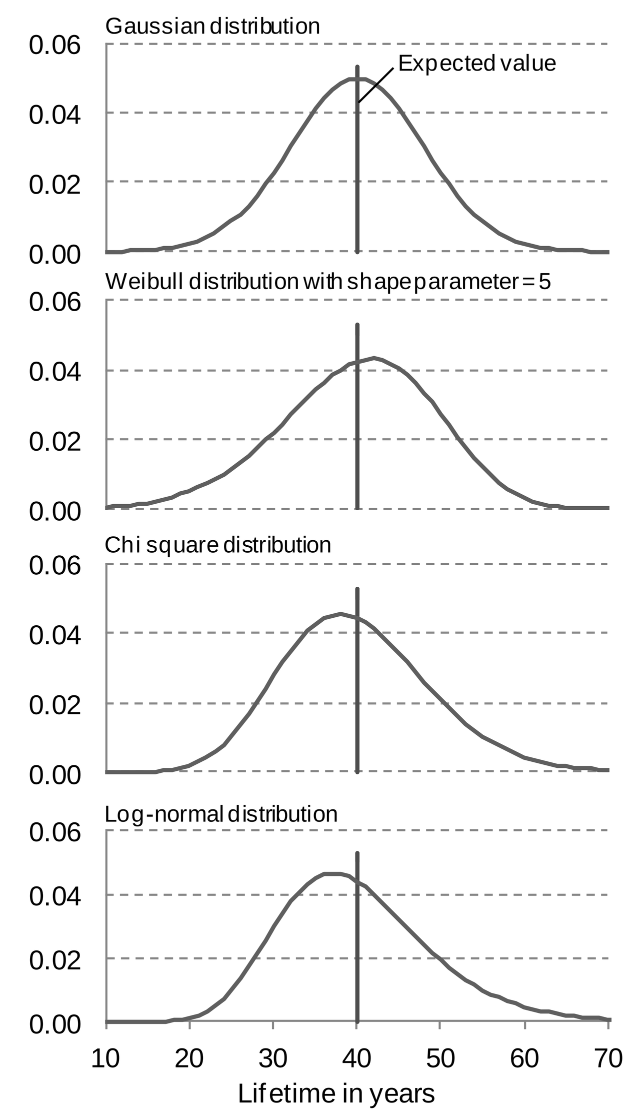

Figure 5 Typical lifetime distributions in safety and environmental engineering

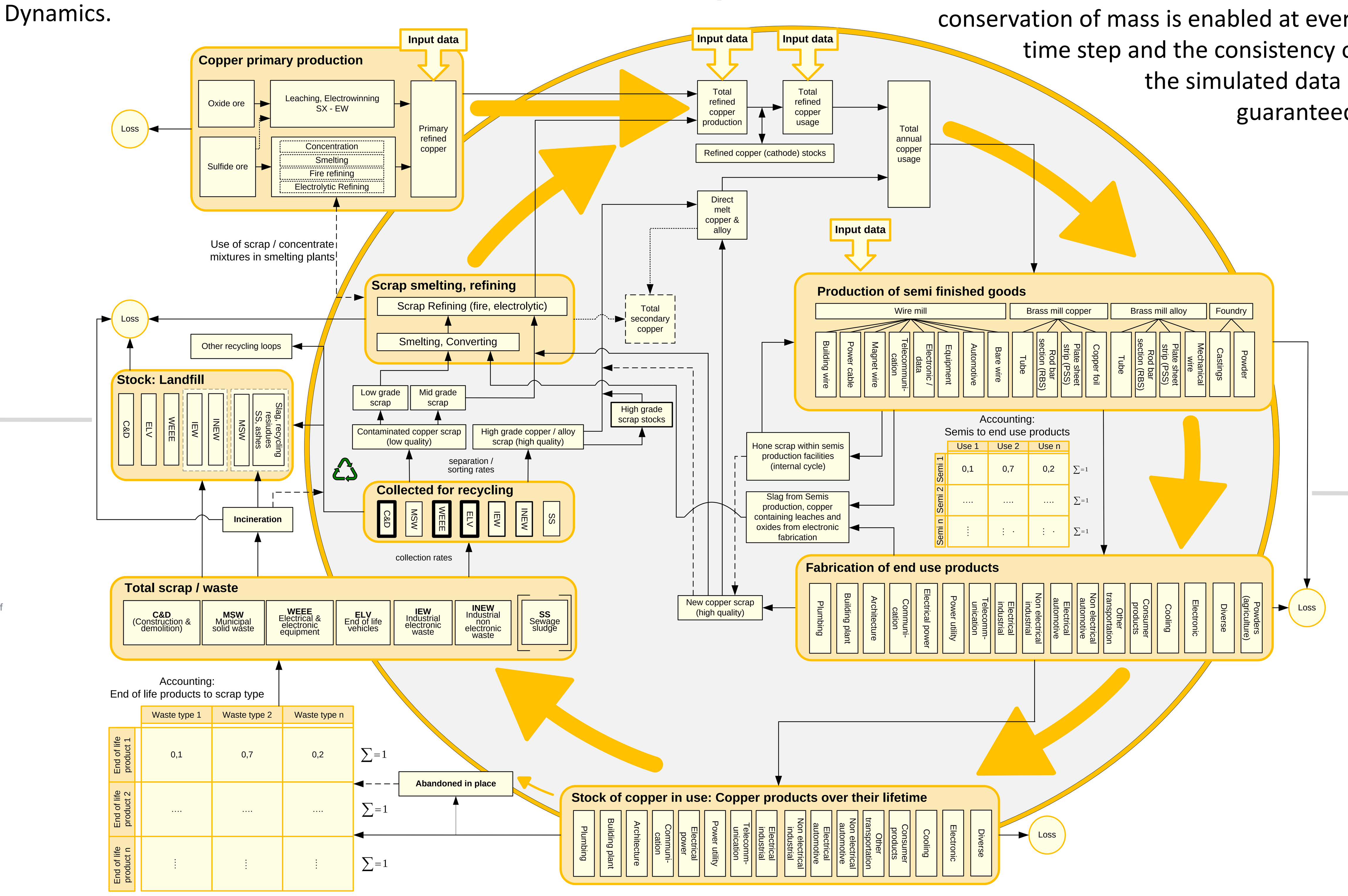

Figure 1: Structure of the global copper flow model

Results: Global Flows of Copper

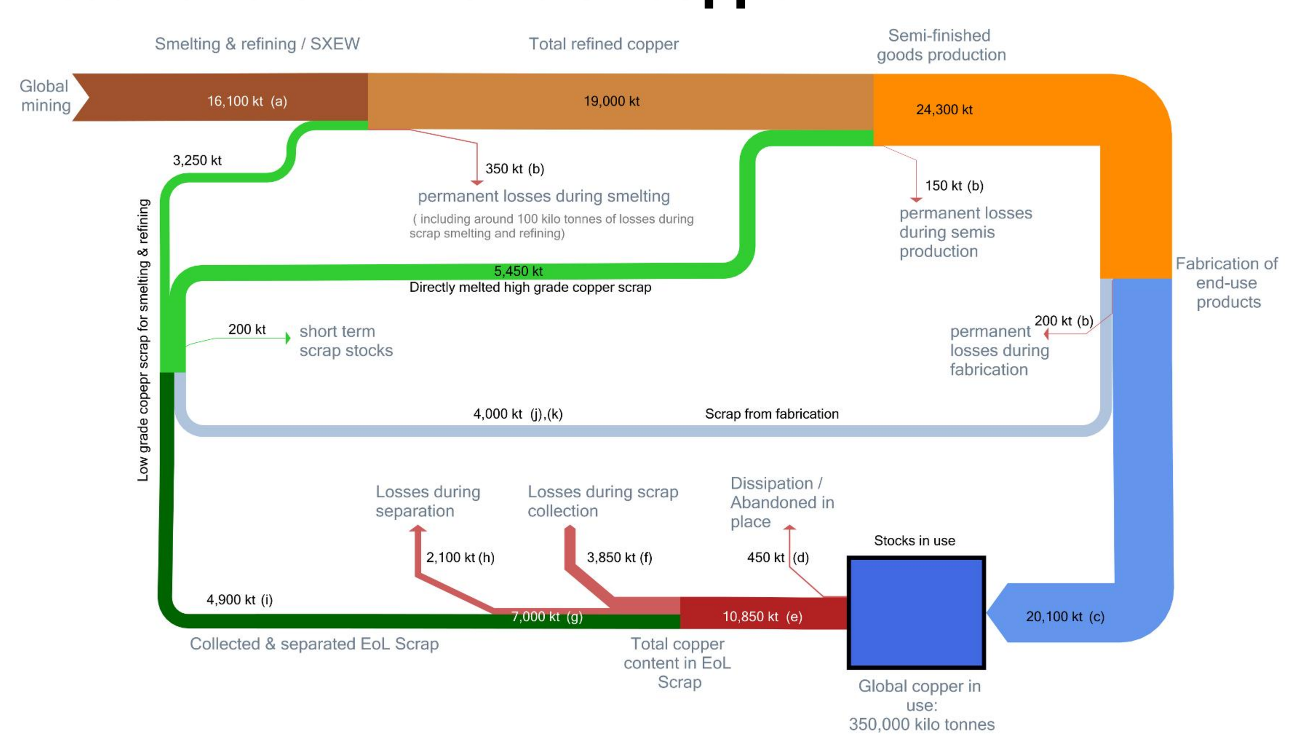

Figure 8 Simplified depiction of global copper flows in 2010 as calculated by the model.

Table 2 Different recycling indicators can be calculated based on the simulated mass flows

Recycling Indicator	Definition	Model Value*
Recycling Input Rate	$RIR=\frac{i+j}{a+i+j}$	35%
EoL Recycling Input Rate	$EoL\ RIR=\frac{i}{a+i+j}$	18%
EoL Collection Rate	$EoL\ CR=\frac{g}{e}$	63%
EoL Processing Rate	$EoL\ PR=\frac{i}{g}$	68%
EoL Recycling Rate	$EoL\ RR=\frac{i}{e}$	43%
Overall Processing Rate	$Overall\ PR=\frac{i+k}{g+j}$	80%
Overall Recycling Eff. Rate	$Overall\ RER=\frac{i+k}{e+j}$	60%
Old Scrap Ratio	$OSR=\frac{i}{i+k}$	53%

*Differences may occur due to simplified depiction and roundings in the Sankey diagram

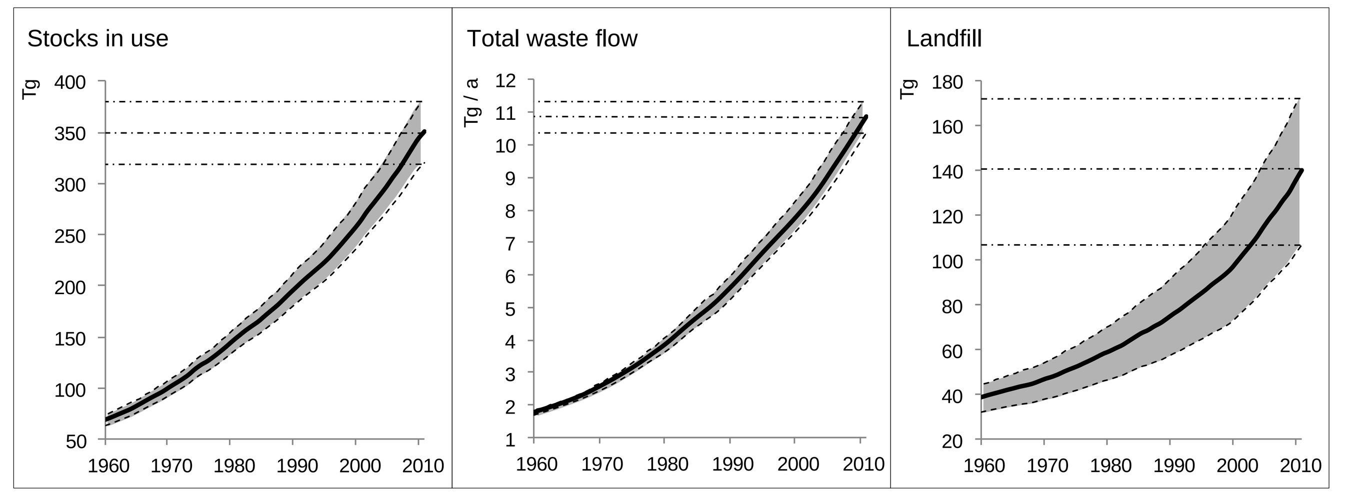

Figure 7 Compared to static approaches a dynamic model provides useful additional data such as material accumulations over time.

Uncertainty Evaluation : Stochastic Simulations

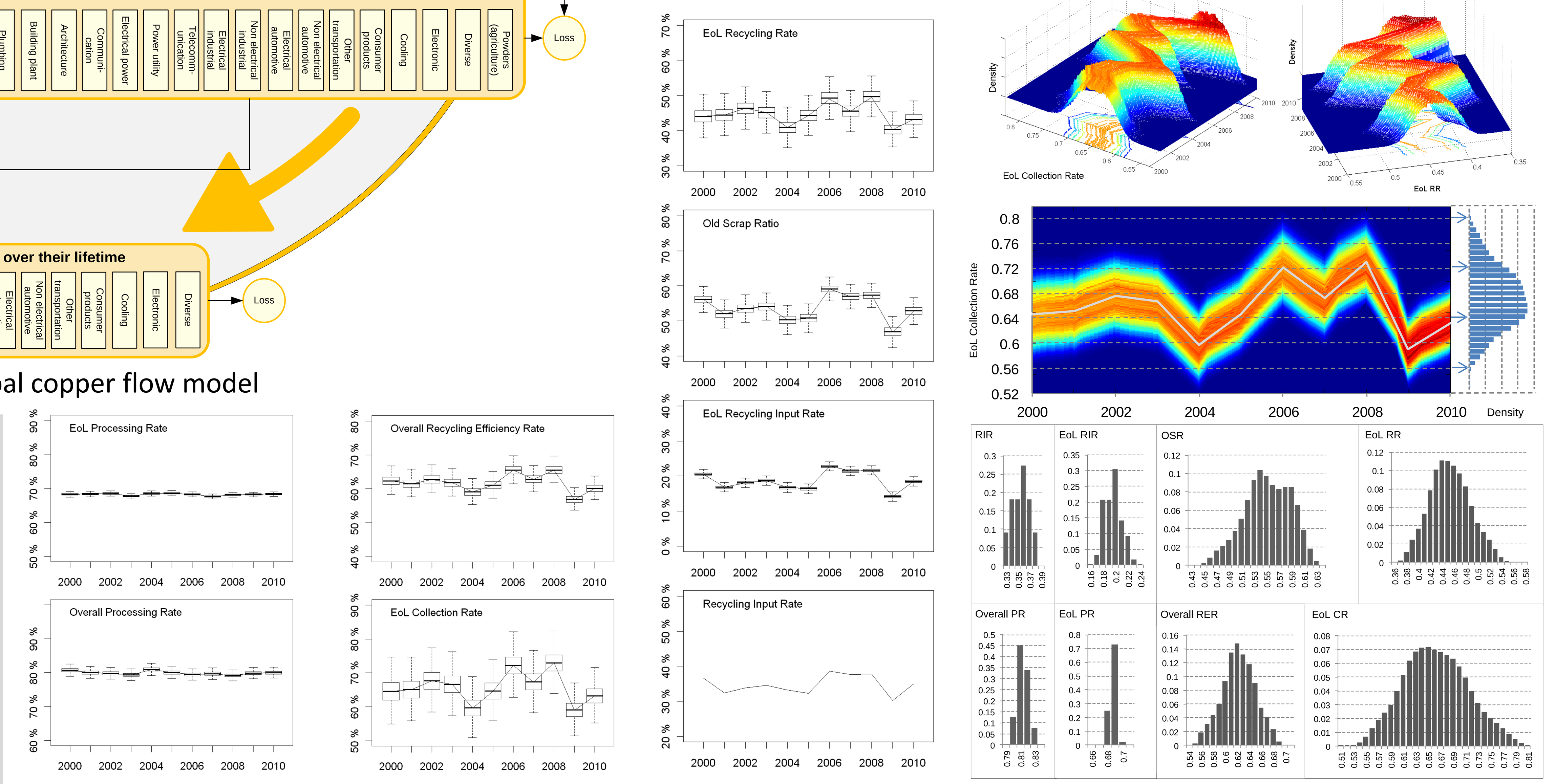

Figure 6 Results of the stochastic uncertainty evaluation for the 8 recycling indicators defined in Table 2

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