Establishment of a Model of Material Stock Saturation in Japan

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Long-term studies in the field of economy-wide material flow analysis (MFA) have so far focused on the flow of materials into and out of the anthroposphere, and less research has been conducted into the long term stock of materials. Construction materials, such as cement, asphalt, timber, and metals, become stocked in the anthroposphere as buildings and infrastructure and remain as stocks longer than other material categories. This research presents a model of the accumulation of material stocks in Japan in the period of 1927-2005 using flow statistics. The results show that in the period of study material stocks have multiplied by a factor of fifty in parallel with post-war Japan's rapid industrial and economic growth. The composition of material stock has remarkably changed during this period resulting in a decline in the share of timber as construction material and the overwhelming increase of non-metallic construction minerals. It was also found that despite economic and material input slowdown since the 1970s, material stock growth has only started to reduce its pace in recent years, and our future projections hint that this decline will continue towards a saturation of material stock levels.

Key Words : *material flow analysis (MFA), construction material stocks, material saturation, industrial ecology, social metabolism*

1. INTRODUCTION

Continuous flows of materials are required to sustain and develop national economies. The inflows of materials from the environment become physical stocks for certain lifespans before being ejected as wastes. These flows and stocks of materials between the natural environment and human society (the anthroposphere) are referred to as social metabolism. Material flow analysis (MFA) is the systemized accounting and examination of the volumes and composition of materials during their transitions into and out of the human economy. It is used to clarify the complex system of material requirements, usage, and disposal by humans, and these factors' relations with the natural environment. It thus provides a decision support tool for resource management, waste management, and environmental management[1)]. Economy-wide MFA studies describe the material requirements of entire countries and regions, allowing comparisons between different countries based, for example, on the inflow of materials[2)] and the outflow of materials[3)]. Standard terminology and accounting methods have been published[4)] and used. Accounting and analysis of material flows for long time periods have been carried out for several countries including the U.K.[5)], Japan[6)], the U.S.A.[7)] and the Czech Republic[8)]. These studies suggest that as economies mature, less material *flow* is required to maintain the economy. However, do the same positive developments occur with material *stocks* as well? What are the relations of economies and material stocks?

So far, long-term research of material stocks has not been carried out. The reason for this might be the lack of stock statistics compared to flow statistics. Calculating stocks from material balances, i.e. subtracting outputs from inputs, is a standard technique employed to estimate stock quantities, for example, in the Japanese Government's official

MFA publications[9], but might result in double accounting[4]. Other techniques of stock estimation have been used. Hashimoto et al.[10] have estimated the stocks of construction materials in Japan based on the amount of structures and their material intensities (the quantity of materials required in a construction activity) of buildings and infrastructure in Japan, and Tanikawa et al.[11] have implemented four-dimensional GIS analysis. These studies

The long-term material flow studies mentioned previously offer new possibilities for the estimation of stocks. This research proposes a model of the accumulation of material stocks based on the inflow statistics of materials in Japan. As described in the next sections, we chose to focus on certain material categories from the established long-term material database of Japan which are used in the construction of buildings and of infrastructure (roads, railways, tunnels, bridges, and so on). We model the accumulation of these specific materials based on their contribution to stock on a yearly basis, including the gradual aging and expulsion of these stocked materials. To the best of the authors' knowledge no lifespan data for these materials as stocks in Japan is currently available, although lifespan statistics exist for buildings[12] and infrastructure[13]. Assuming that structures and the materials composing them should have the same lifespans, we used generalized values of these figures for the modeling of the materials' aging processes.

Japan has undergone exceptional development in a relatively short time during the 20th century, rapidly growing into a fully industrialized society within decades. The scope of this research, from 1927 to 2005, includes several important periods in Japan's economic history which provide an interesting record of accumulation of material stocks to examine.

In the following sections, we present the data sources used in this study, the framework of the model, and the methods used for estimating the stocks. The results of estimation are then presented for the past and the for the future, including the changes in composition of stocks followed by a discussion on the growth of stocks in relation with changes in population and the economy. The conclusion details some implications and possible extensions to this research.

2. DATA AND METHODS

(1) Statistical Data

Long-term data for the inflow of materials in Japan has been compiled by Krausmann et al.[6]. This database contains material flow statistics of 61 material groups based on current MFA standards. The advantage of this database is in the long time range that it covers, from 1878 to 2005. This timeframe encompasses Japan's transition from a mainly agrarian society to today's modern one, including such milestones as the Meiji Restoration, pre-war period, World War 2, the rapid growth phase in the post-war era, the slowdown of growth following the oil shocks of the 1970's, and the recovery period following the economic bubble of the early 1990's. It should be noted that the model presented in this paper starts in 1927 because of methodological reasons described in the next section.

Out of the material groups documented in this database, materials used for construction of buildings and infrastructure were extracted to be used in this study. Construction materials comprise the vast majority of material stocks and remain stocked in the anthroposphere in the range of decades, much longer than other material categories such as fossil energy carriers and biomass, which are used and discharged within a few years or less[3].

For the current research, the four major construction-related materials categories were extracted from the MFA database:

1. timber
2. iron
3. other metals
4. non-metallic minerals

The non-metallic minerals category includes such materials as stones, sand, limestone, gravel, and clay. The material flow data in the database is provided as yearly statistics, divided into domestic extraction, imports, and exports.

Figures concerning the mean lifespan of construction materials were adapted from building and infrastructure lifespan data[12,13], based on an assumption that the lifespan of construction materials is similar to the lifespan of structures composed of them. The main purpose of the current study is to analyze the trends of material stocks on the national scale, some generalizations and simplifications were made to these parameters that are deemed acceptable, since different values have a weak effect on the overall trends. Population and GDP data was taken from the work of Maddison[14].

(2) Methods of estimation

The framework of this model maintains the four above mentioned material categories throughout the metabolic processes of input, stock, and output. Input for each material is based on the statistical data extracted from the material flow database of Japan. Each yearly input is considered a new "layer" of material added to the existing stock from past years. The quantity of material of each composing layer is reduced through a process of aging, estimated using a survival function in yearly calculation steps, modeling the gradual aging and output of materials that was input in different years. The framework is illustrated in fig. 1.

The actual amount of material directly used for construction by the economy in a year is given by the following equation, based on Eurostat[4]:

$$MC_i(t) = DE_i(t) + IM_i(t) - EX_i(t) \tag{1}$$

Where $MC_i(t)$ is the amount of material consumption of material i in year t; $DE_i(t)$ is the domestic extraction of material i in year t; $IM_i(t)$ is the import of material i in year t; and $EX_i(t)$ is the export of material i in year t;

For each category, the material consumption values contain a mix of raw and processed materials, semimanufactures, and final products. Moreover, the percentage of material that is used for construction and for other types of consumption is different, and some of the materials that are used for the construction of buildings and infrastructure become waste during construction and do not remain as stock in the completed structure. The actual amount of input material that becomes stocked is calculated by the following formula:

$$AS_i(t) \ = \ MC_i(t) \times r_i \tag{2}$$

Where $AS_i(t)$ is the new "layer" of addition to the total stock of material i in year t; and r_i is the rate of material i that is stocked as constructed structures in the anthroposphere. The assumed values of r_i are given in table 1.

Structures age and eventually get demolished, and their constituting materials are considered output from the economy as wastes. The amount of surviving material in a layer of stock is estimated by the following function:

$$RS_i(t,\tau) \ = \ AS_i(t) \times \left(Q\left(\frac{(\tau - t) - \mu_i}{\sigma_i}\right)\right) \tag{3}$$

Where $RS_i(t,\tau)$ is the stock of material i that was constructed in year t which remains in year $\tau(> t)$; Q is the Q-function, the complement of the standard normal cumulative distribution function $\Phi(x)$, i.e. $Q(x) = 1 - \Phi(x)$, providing the probability of survival of material i constructed in year $\tau(> t)$ after $(\tau - t)$ years have passed. μ_i is the mean lifespan of material ; and σ_i is the standard deviation of material i. The assumed values of μ_i and σ_i are shown in table 1, as discussed in the previous section.

Table 1 Assumed rate of stock of materials and variables for estimating the probability of survival of material. Lifespan values adapted from [12,13]

	Rate of input into stock (r_i)	Assumed Mean lifespan (μ_i)	Assumed Standard Deviation (σ_i)
Timber	90%	30	10
Iron	20%	50	16.666
Other Metals	10%	50	16.666
Non-metallic minerals	90%	50	16.666

The total amount of stocked material is estimated by the following formulas:

$$MS_i(\tau) = \sum_t RS_i(t,\tau) \tag{4}$$

$$MS(\tau) = \sum_i MS_i(\tau) \tag{5}$$

Where $MS_i(\tau)$ is the stock of material i in year τ; $MS(\tau)$ is the total stock of construction materials in year τ.

Since no base material stock data is available the stock materials starts at $MS(\tau = 0) = 0$. Therefore the period $1 \leq \tau < \mu_i$ is regarded as a buffer for the accumulation of materials in the model and should not be considered as reflecting actual stock in these years.

The projection of material stocks figures from 2005 to 2030 is modeled with the same methods, assuming a steady input based on the average of the

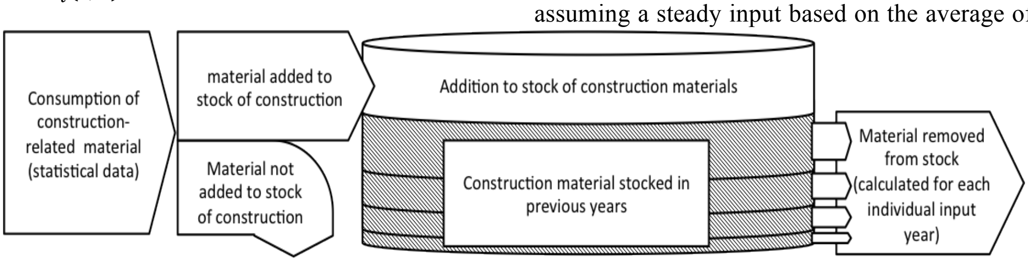

Fig.1 Model framework of flows and stocks in a given year

material input of the last 10 years of the dataset for the next 25 year period.

3. RESULTS AND DISCUSSION

(1) Development of material stocks

As shown in fig. 2, in a period of nearly 80 years the total stock of construction materials in Japan grew from 743 million tons in 1927 to 38.3 billion tons in 2005- more than 50-fold. The trend of change is characterized by slow growth in the first period up to the 1950's, consisting of the pre-war period, World War 2, and the occupation era; and then a massive increase of stocks in the decades of Japan's rapid economic growth phase. In recent years there is an apparent slowdown of this growth. Assuming a future inflow of construction materials similar in quantity to the average of the last decade, the increase of overall stocks will continue to slow down, implying an s-shaped growth curve for material stocks, perhaps leading towards a saturation of stocks. Nevertheless, in the next 25 years a total halt to growth is not foreseen.

The changes in material stock trail the trends of inflow of materials, whose growth period has largely ended by the oil shock of 1973. The quantity of input materials has been fluctuating in the next two decades and since peaking in 1991 there has been a general downward trend. Thus the decline of growth of material stocks in recent years can be attributed to the fact that more and more of construction that was built until the 1970's is reaching its end of life and is being demolished, but without the same rates of input less material is stocked. Thus the declining amounts of input several decades ago are only starting to show up now in the quantities of material

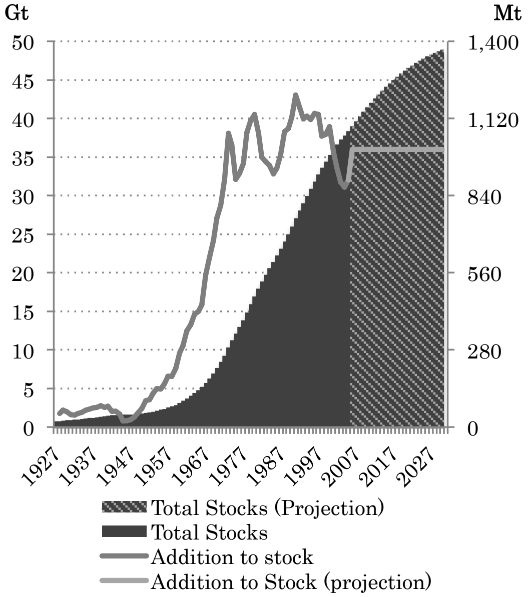

Fig.2 Construction material stocks in Japan, 1927-2030. Left axis: Total material stocks. Right axis: additions to stock.

stock.

The trends of each material category are illustrated in fig. 3. The three material categories of iron, other metals, and non-metallic minerals have all been rapidly increasing in conjuncture with Japan's economic growth phase since the beginning of the 1960's. Iron stocks in construction in 2005 were 162 times the stock quantities of 1927, the biggest increase rate of the four examined categories. The quantity of minerals stocked in construction has multiplied by a factor of 63 in the study period and the category of other metals has grown 13-fold. This category is also predicted to reach a saturation in the near future. Opposed to the constant growth of these

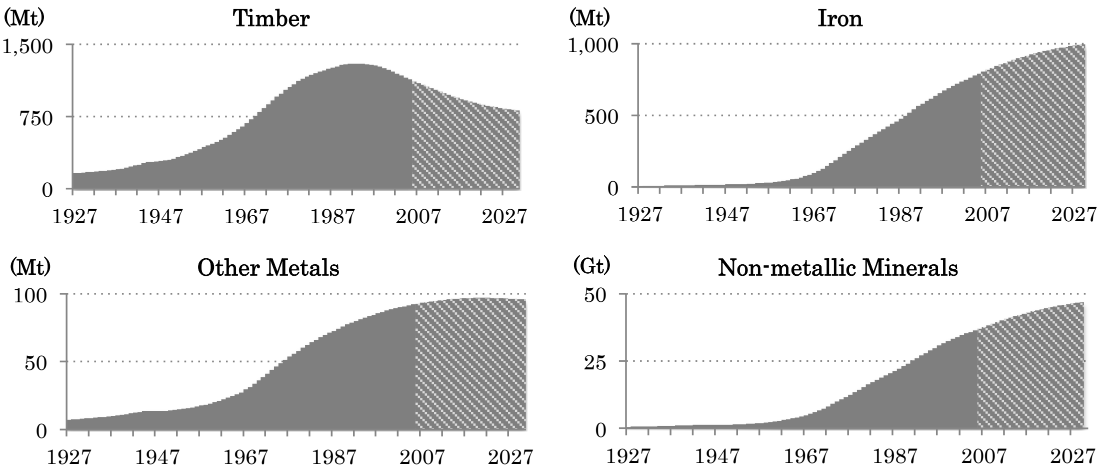

Fig.3 Individual stocks trends of timber, iron, other metals, and non-metallic minerals, 1927-2030. Note different scale of non-metallic minerals.

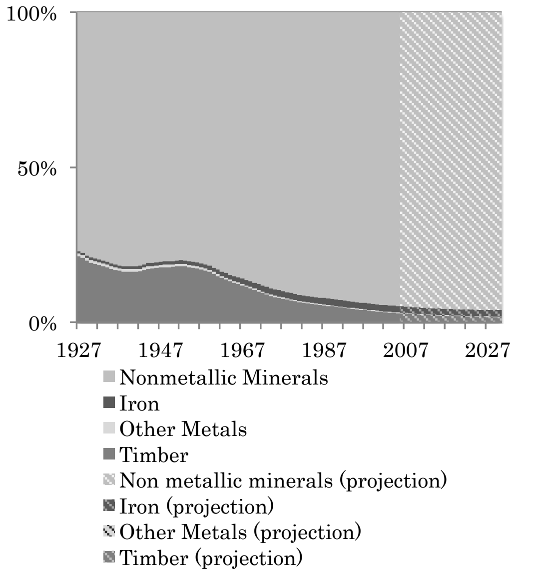

Fig.4 The composition of material stock in Japan, 1927-2030.

three material categories, timber stocks reached a peak of 1.3 billion tons in 1993 and have been decreasing since then. A stabilization of the stock of timber is predicted to occur at a quantity of 0.8 billion tons in the 2030's.

(2) Composition of stock

The composition of material stocks, shown in fig 4, has evolved over the examined time period, revealing the changes in preferred construction materials and technologies over the 20th century in Japan. Since 1887 the yearly *inflow* of non-metallic minerals has been greater than the inflow of timber, Japan's traditional construction material. Consequently, throughout the examined period of 1927 onwards, the major constituent group of construction stocks is non-metallic minerals. The share of these materials has risen from 77% in 1927 to 95% in 2005 and is expected to rise to 96% by 2030. In comparison, timber consisted 21% of total material stocks in 1927 but declined to 3% in 2005. It is interesting to note that during in the immediate post-war period of recovery, timber regained part of its share back to 18%, but since then has constantly diminished, and is projected to reach 2% by 2030. The share of metals has been small during the entire study period. Iron has increased from 1% to 2% by 1964, and remained at that rate since then, while the share of other metals has consistently been under 1%.

(3) Dynamics of growth

Since the beginning of the 20th century, and specifically after World War 2, Japan's economy has rapidly risen to become the world's 3rd (and until recently, 2nd) largest economy. In the study period Japan's population has doubled from 61.5 million people in 1927 to 127.5 million in 2005. In that period GDP per capita increased from 1,869 Geary-Khamis dollars (also known as international dollars) to 21,976 dollars, an 11-fold rise. The comparison of Material stocks per capita to GDP per capita is shown in fig. 5. Material stocks per capita have increased approximately in parallel to GDP per capita until the beginning of the 1970's, in which the growth of the two indicators decoupled. Since the oil shocks of that decade, Japan's economic growth has slowed down, however a similar trend has not occurred to the development of material stocks, whose growth has continued at a similar rapid pace until the end of the 20th century, and only in recent years has started to show signs of slowing down.

The sustained rapid increase in material stocks can be attributed to several factors. First, Japanese building standards are periodically updated to regulate increased material intensity due to Japan's susceptibility to natural disasters such as earthquakes[11)], requiring more material input into each new or replaced structure. A second reason could be the growing affluence of Japanese society, creating demand for bigger and higher quality construction. Given Japan's relatively short average building lifespan[11)], the number of new, higher-quality construction can help maintain the rate of stock increase. Thirdly, nationwide infrastructure projects such as high speed rail, dams, and national highways have been constantly expanding. Japan's rugged mountainous terrain necessitates vast numbers of bridges, tunnels, and other material-intensive civil engineering structures to support these kind of projects, which contribute to the increase in stocks. A fourth reason could be that some of the stock included in this calculation is actually dissipated stock such as disused buildings and infrastructure, which still "hibernate" in the anthroposphere but have no meaningful contribution to the economy[15,16)].

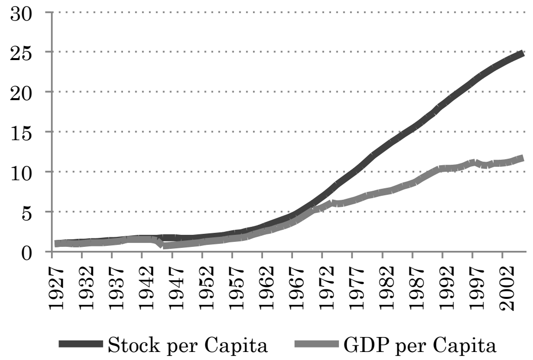

Fig.5 Stock per cap vs. GDP per cap. 1927 = 1.

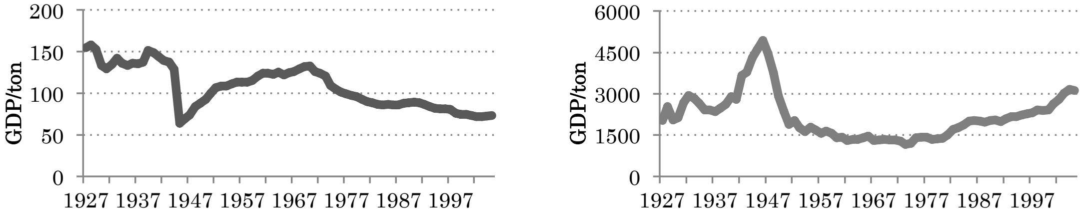

Fig.6 Left: Construction material stock productivity 1927-2005. Right: Construction material input productivity 1927-2005.

The material stock productivity (defined as GDP per ton of stock) can be separated into several distinct periods (fig. 6). The first, from the beginning of the time series (1927) to the end of World War 2, is characterize by the highest rate of material productivity in the study period. The collapse of the Japanese economy following its defeat in World War 2 is clearly shown in the figure, leading to a major drop in stock productivity. The Japanese economy has quickly recovered and stock productivity rose back in the next three decades, though not reaching the same high values of the previous period. 1969 was the peak year of material stock productivity in post-war Japan, and since then productivity has been constantly decreasing.

4. CONCLUSIONS

Over the timeframe that the study period covers, Japan has undergone tremendous social, economic, and cultural changes. The model presented in this research provides results are in the same order of magnitude and general trends found in previous research[10,16], while extending the scope of study period tremendously. Some assumptions have been made such as the rate of stocking of materials, the mean lifespans of materials as stocks, and their standard deviations. However, it should be noted that direct experimentation with these figures revealed that changes in these values, while affecting the figures of stocks, do not affect the trends of growth or the orders of magnitude presented in this paper. Future work will focus on refining these figures.

The model shows that material stocks have increased much faster than both the population and the economy during this time. The rise of Japan's economy in the second half of the 20th century has been a model to other countries in East Asia and beyond. From an environmental point of view, will global natural resources enable populous countries such as China, India, or Indonesia to follow a similar development curve? What would be the ramifications? The model developed in this study offers a relatively simple method that will enable estimation of nationwide material stocks for these countries as well.

As mentioned above, the trends of material stock productivity have been decreasing during the study period. These trends are almost inverse to the trends of material input productivity (the amount of GDP per ton of construction material input). The material input productivity of construction materials has been rising in recent decades (fig. 6). This is part of a trend of increased productivity of all input materials suggesting a process of dematerialization in Japan[6] thanks, in part, to the *sound material society* official policy of the Japanese government[9].

However, changes to material stocks behave, by their nature, similar to population figures, in a slow and gradual fashion. Reduction of inputs, whether caused by reduced economic activity, declining population, or by policy, will only affect the quantification of stocks years later. Construction materials remain in the anthroposphere for long periods and thus it should be no surprise that stock productivity has not improved as readily as material inputs. Nevertheless, actual productivity might be different when considering functional stock vs. disused stock that is of no use to the economy, and future study should focus on this question.

Furthermore, while inflow of construction materials are affected by mechanisms such as policy and economic forces, ordinarily the outflow of construction materials is a constant, gradual flow, and is handled by this model as such. Nevertheless, outflow singularities of massive ejection of material stocks can occur in events of wars and natural disasters such as earthquakes and tsunamis, all of which have actually struck Japan during the study period. Future modeling efforts should take these kind of events into account.

The projections presented in this study suggest that under current inflow conditions growth of stocks will continue to slow down, hinting that Japan might be approaching material stock saturation. However, it is not clear whether the growth trend is leading towards stable levels of material stock quantities, or towards an absolute decrease of material stocks. Further investigation into the future stocks of materials is required.

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