INDICATORS OF MATERIAL FLOWS: CONCEPTUAL FRAMEWORK, USE AND ASSESSMENT OF TRENDS IN THE CZECH REPUBLIC

1. Socio-economic metabolism

In order for an economic system to function and produce goods and services necessary for meeting human needs, it behaves similarly to a living organism. It absorbs substances from the surrounding environment and transforms them into products, but ultimately all the materials are transformed into some kind of waste and emitted back into the environment. The economic system above all absorbs fossil fuels, other mineral resources, biomass and water on the input side while emits emissions to the air, water and solid wastes on the output side. This flow of materials is referred to as an industrial or socio-economic metabolism (Baccini and Brunner, 1991; Fischer-Kowalski and Haberl, 1993; Ayres and Simonis, 1994).

The theory of socio-economic metabolism considers socio-economic system to be a sub-system of the environment connected to its surroundings through energy and material flows. These flows burden the environment and along with land use and other biological and social factors they belong to the key source of environmental problems. If the volume of these flows was reduced, a decrease in environmental pressure could be expected (Schmidt-Bleek, 1993; Bringezu et al., 2003; Weizsäcker et al., 2009).

Environmental pressure is already related to the extraction of mineral resources. The crude oil extraction involves leakages both during extraction phase and oil transportation. The negative impacts on the environment take place during the underground and surface extraction of minerals as well (Neužil, 2001). These impacts include air emissions (mostly of CO, CO_2, SO_2, SO_3, CH_4, NO, NO_2, and PM), disturbance of water regimes and water contamination, land appropriation and contamination, direct disturbance of biotopes, noise, vibrations and changes in landscape. Other pressures are related to pre-processing of minerals – sorting, crushing, rinsing and drying.

Much bigger environmental burden is related to the consumption of mineral resources. It is besides others caused by the fact that while number of mineral resources entering the economic system is limitted, the number of pollutants emitted due to the consumption of minerals has been growing (Spangenberg et al., 1999). Moreover, these pollutants enter the environment by huge number of gateways: each dumping place, each smokestack and each exhaust pipe presents such a gateway. Consumption of mineral resources contribute, for instance, to global climate change, depletion of stratospheric ozone, eutrophication, acidification, radioactive pollution, etc. (Giljum et al., 2005).

The environment is able, to some extent, to neutralize the environmental pressure imposed on it by human society in relation with the consuption of materials. If the rate of use of renewable resources is lower than the rate of their renewal, or wastes are emitted in such volumes, which can be absorbed by the environment, any severe damage to the environment should not take place (Bringezu and Bleischwitz, 2009). This rate is, however, often exceeded (World Resource Institute, 2005) and there is a problem with non-renewable resources. Their sustainable rate of use is difficult to determine, above all with respect to their maintenance for future generations.

So far, there has been a positive relation between meeting human needs and pressure exerted on the environment. When standards of living went up, this pressure was growing as well, even though it was often shifted abroad in the case of developed countries (import of resources or transfer of "dirty" industries to developing countries). The environment of developed countries was thus cleaned up (Giljum et al., 2009; Schütz et al., 2004). On the global level, however, the human society recorded an unprecedented growth in annual material and energy inputs and outputs over the 20th century (Krausman et al., 2009). As argued above, this was also accompanied with the growh of environmental pressure. Developed countries within their strategies of sustainable development therefore adopted a goal to break the relation between pressure exerted on the environment and economic growth, i.e. to meet human needs and improve the standard of living. This phenomenon is shortly called decoupling (from longer "decoupling of environmental pressure from economic growth") (Fischer-Kowalski et al., 2011; OECD, 2002).

2. Economy-wide material flow analysis, meaning and use of material flow indicators

Material flow analysis belongs among the methods, which allow for quantification of socio-economic metabolism and assessment of environmental pressures related to the use of materials. Nowadays, the attention is drawn to economy-wide material flow analysis (EW-MFA). EW-MFA was developed during the 1990s by various research institutes and organizations (principally the World Resources Institute, the

Wuppertal Institute for Climate, Environment and Energy, the Department of Social Ecology at the Faculty for Interdisciplinary Studies of the University in Klagenfurt, Japanese National Institute for Environmental Studies, and Eurostat). Afterwards, EW-MFA was standardized in methodological guides of Eurostat (Eurostat, 2001, 2018).

The Czech Statistical Office focused on compilation of indicators of material input and material consumption. These are the best developed ones from the methodological point of view and are based on available data. Methodology for their compilation is described in the methodological chapter. Below is the summary of their possible uses (OECD, 2008):

Overall physical scale of the economy and total environmental pressure related to use of materials
To study overall physical scale of the economy over time, it is advisable to refer to material flow indicators in absolute terms. These indicators are considered proxies for environmental pressure related to use of materials and energy.

Equity and equal resource sharing
Relating material flow indicators to population allows for a comparison of material use and disposal of pollutants from the viewpoint of equity and equal resource sharing. Generally speaking, all people should have equal rights to consume natural resources and use the environment for assimilation of waste flows (Moldan (ed.), 1993).

Land use intensity
Consumption of materials can be related to the area needed for materials production. This issue has above all been developed for renewable resources and is well-known as a concept of Ecological Footprint (Wackernagel et al., 1996) and Human Appropriation of Net Primary Production (Vitousek et al., 1986). For cities, area for production of consumed materials is always larger than the area of a particular city. This is caused by high population density and low share of bioproductive areas. For countries and regions, the situation may be reverse.

Efficiency of use of materials and decoupling of environmental pressure from economic growth
Relating input and consumption material flow indicators to national account aggregates, such as gross domestic product (GDP), allows for measuring the efficiency by which an economic system transforms used materials into economic output. Such indicators reflect material productivity, i.e. the ratio of GDP over the material flow indicator, or material intensity, i.e. the ratio of the material flow indicator over GDP. These two measures are compatible with the inverse time development.

Assessment of material intensity and productivity is complementary to analysis of decoupling of environmental pressure from economic growth (see text above). Decoupling can be relative or absolute. When a relative decoupling occurs, there is a decrease in material consumption per unit of GDP, but the absolute material consumption is still growing. When an absolute decoupling occurs, the economy is growing while the absolute volume of resource consumption goes down. We should aim at absolute decoupling, as total environmental pressure is determined by absolute material consumption.

Shifting of environmental pressure between states and world regions
Many industrialized countries have decreased their amounts of domestically extracted and processed materials by importing them from other countries. The shift of pressure related to extraction and processing of these materials has taken place between states and world regions mainly to the detriment of developing countries (Giljum et al., 2009; Schütz et. al., 2004). To capture these shifts, it is necessary to study physical imports and exports and related flows.

Foreign material dependency and material security
Material flow indicators can be further used for monitoring of foreign material dependency. Economies fulfil their material demands partly from their own territory and partly by importing materials from other countries. The higher the share of imports in domestic material input and domestic material consumption is, the more the economy is susceptible to incidental shortage of particular commodities abroad, increase in their price or to upheaval of other barriers to foreign trade.

Potential for future waste flows
All input material flows, which are going to be accumulated in form of physical stocks, will change into waste flows sooner or later. Knowing the volume of physical stocks in particular cities, regions and states and their durability, one can model waste flows to come. This is useful for planning of capacities for waste treatment within the waste management plans both in short, medium and long-term perspective.

Use of renewable and non-renewable materials
It is acknowledged internationally that the sustainable supply of materials should be based on renewable materials to a certain extent. This refers not only to scarcity of non-renewable materials but also to the fact that use of non-renewable materials is generally linked to comparatively higher negative impact on the

environment (EEA, 2006). This issue can be captured by input and consumption material flow indicators by monitoring ratios of renewable materials in particular indicators.

3. Assessment of development of selected material flow indicators in the Czech Republic in 2014-2019

The used domestic extraction went up by 4.8% from 157.7 million tonnes to 165.3 million tonnes in 2014-2019 (Table 1). An increasing trend of used domestic extraction was visible over the whole monitored period with the exception of years 2016 and 2017 when a slight decrease occurred from 160.1 million tonnes in 2015 to 159.8 million tonnes in 2016 and 158.6 million tonnes in 2017. It is meaningful to relate used domestic extraction to the area of the Czech Republic – it expresses pressure coming from the extraction of resources exerted on one unit of the country's area. This pressure increased from 1 999 tonnes per km^2 to 2 096 tonnes per km^2 in 2014-2019. The pressure covers structural changes of landscape related to extraction of non-renewable resources (moving of overburden, undermining) and pressures on biodiversity and land use in the case of extraction of renewable resources (above all when producing biomass in large-scale agro-ecosystems).

Breakdown of used domestic extraction by groups of materials shows that the overall increase was caused both by non-renewable and renewable resources, which went up by 3% from 119.7 million tonnes to 123.2 million tonnes and by 10.6% from 38 million tonnes to 42 million tonnes, respectively. Regarding non-renewable resources an increase was recorded for industrial minerals, which went up by 2.7% from 11 million tonnes to 11.3 million tonnes and construction minerals, which increased by 15.6% from 61.5 million tonnes to 71.1 million tonnes. On the other hand fossil fuels decreased by 13.2% from 47 million tonnes to 40.8 million tonnes. The extraction of metal ores, which only included extraction of uranium ores, was totally suppressed and went down by 100% from 137 thousand tonnes in 2014 to zero in 2018. In the case of renewable resources there was an increase in biomass from forestry, which grew by 91.2% from 9.2 million tonnes to 17.6 million tonnes. An increase especially occurred in 2018 and 2019, which could be associated with the ongoing bark beetle calamity. An increase by 32.9% from 13.9 thousand tonnes to 18.5 thousand tonnes was recorded also for biomass from hunting. Two categories of renewable resources went down: biomass from agriculture by 15.2% from 28.7 million tonnes to 24.4 million tonnes and other biomass by 10.7% from 48.2 thousand tonnes to 43.1 thousand tonnes. It should be noted that absolute values of other biomass and biomass from hunting were very low so they influenced the trend of production of renewable resources only insignificantly.

Both physical import and export recorded a growth by 10.6% and 7.8%, respectively, in 2014-2019. The physical import went up from 73.4 million tonnes to 81.2 million tonnes while physical export went up from 70.7 million tonnes to 76.2 million tonnes in this period (Table 2). Physical import can be viewed as a first indication of environmental pressure, which is shifted from importing countries to exporting ones – production of this import is related to environmental pressure in the exporting country (pressure from extraction of resources and production of commodities) and the driving force of this pressure is the importing country, which demands these commodities. Similarly, the physical export indicates shifts of environmental pressure from abroad to the Czech Republic. The shifts of environmental pressure were growing in the monitored period, and this was true both for import and export.

Growth in physical import in absolute values came mainly from metal ores category (raw material, semi-manufactured products and manufactured products from metal ores), which grew by 10.4% from 20.6 million tonnes to 22.8 million tonnes. Growth in physical export in absolute values was mostly influenced by biomass, which went up by 16% from 27.6 million tonnes to 32.1 million tonnes. A quite significant increase in volume of physical import and export was recorded also for all other material categories with the exception of export of fossil fuels (a decrease from 13 million tonnes to 9.7 million tonnes, i.e. by 25.5%) and export of waste, which went down by nearly 100% from 3 300 tonnes to 2 tonnes. Similarly to used domestic extraction of other biomass and biomass from hunting, however, the absolute mass of waste is very small and influences the total volume and trend of physical import (and also of physical export) only insignificantly.

Both DMI and DMC indicators increased by 6.7% from 231 million tonnes to 246.4 million tonnes and by 6.2% from 160.4 million tonnes to 170.3 million tonnes, respectively, in 2014-2019. Expressed in per capita terms, DMI increased from 22 tonnes to 23.1 tonnes per capita and DMC went up from 15.2 tonnes to 16 tonnes per capita (Table 3).

DMI and DMC can be understood as proxies for total environmental pressure related to use of materials in the Czech Republic (pressure related to extraction of raw materials, their processing and output waste flows). The DMC indicator represents pressure, which is driven by the consumption in the Czech Republic while the DMI also comprises pressure, which is driven by consumption in the countries the Czech Republic exports to. The DMC indicator is further interpreted as a waste potential, because all consumed materials will turn into waste sooner or later. This shows the linkage between input and output indicators of material flows and the fact that the only way how to effectively decrease output material flows is to reduce material *consumption. As both DMI and DMC increased in the monitored period, there was an increase in environmental pressure driven by consumption in countries we export to, as well as an increase in environmental pressure related to material consumption in the Czech Republic. At the same time, the potential for waste flows in the years to come was growing.*

Overall trend of DMI and DMC indicators was mostly determined by non-metallic minerals, which went up by 13.8% from 80.6 million tonnes to 91.7 million tonnes in the case of DMI and by 13.2% from 72 million tonnes to 81.6 million tonnes in the case of DMC. The growth was, however, recorded also for other components of the indicators with the exception of fossil fuels, which went down by 5.7% from 73.1 million tonnes to 69.4 million tonnes in the case of DMI and by 1.5% from 60.6 million tonnes to 59.7 million tonnes in the case of DMC. A steady state at the level of approximately 4.5 million tonnes was further recorded for DMC of metal ores. Waste constitutes a special item, which showed a relative increase in both DMI and DMC by hundreds of percent, but their absolute increase is small (by 1 511 tonnes and by 4 809 tonnes, respectively). Since physical export is significantly higher compared to physical import for waste in 2014, DMC indicator shows a negative value for this material category in this year. From the viewpoint of DMI structure, there was a decrease in shares of fossil fuels and an increase in shares of all other material categories. Regarding DMC, it recorded a decrease in the share of fossil fuels, but also in the shares of biomass and metal ores (Tables 4 and 5).

Share of renewable resources (biomass) in DMI went up from 22% to 22.7% in the monitored period, but a decrease from 14.5% to 14.1% was recorded for the biomass share in the case of DMC. Taking into account that consumption of renewable resource is usually related to lower environmental impacts, this trend can be considered favourable for DMI, but unfavourable for DMC. Also a decrease in share of fossil fuels is favourable, since consumption of fossil fuels is related to emissions of greenhouse gases, which contributes to global climate change. The share of fossil fuels in DMI and DMC went down from 31.9% to 28.2% and from 37.8% to 35.1%, respectively, in 2014-2019.

Material intensity expressed as DMI to GDP ratio went down by 11.1% from 52.6 kg per 1 000 CZK to 46.8 kg per 1 000 CZK, material intensity expressed as DMC to GDP ratio decreased by 11.5% from 36.5 kg per 1 000 CZK to 32.3 kg per 1 000 CZK in 2014-2019. Material productivity expressed as GDP per DMI and DMC, which time development is an inverse of the time development of material intensity, went up by 12.5% from 19 kg per 1 000 CZK to 21.4 kg per 1 000 CZK in the case of DMI and by 13% from 27.4 kg per 1 000 CZK to 30.9 kg per 1 000 CZK in the case of DMC (Tables 4 and 5). It can be assumed from the decrease in material intensity and the increase in material productivity that the efficiency by which an economic system transformed used materials into economic output was growing and that there was a decrease of environmental pressure per unit of GDP. This was allowed by implementation of modern technologies, changes in structure of the economy and by an increase in recycling. Moreover, it is also possible to assume a growing competitiveness due to decrease in production costs related to purchasing of raw materials and other materials needed for production. There is currently a discussion if GDP is a proper indicator to calculate material intensity and productivity. In order to maintain consistency an indicator should be used, which contains similar items in monetary units that are comprised in material flow indicators in physical units. Alternative indicators to GDP, which are mentioned in these discussions include, for instance, economic output or GDP plus import for DMI and GDP plus import minus export for DMC (OECD, 2008; Hirschnitz-Garbers et al., 2014).

DMI and DMC indicators can be represented in a single graph together with GDP, when an index value of 100 is attributed to all indicators for the starting year and the percentage change of this index is shown for the following years. This allows for expression of decoupling of environmental pressure (represented by DMI and DMC, respectively) from economic growth (represented by GDP) (Graph 10), which is mentioned in the previous chapter. There was a relative decoupling in the Czech Republic in 2014-2019 in the case of DMI and DMC: both indicators went up, but less than GDP. This development can be considered favourable, but it is necessary to achieve an absolute decoupling for an absolute reduction of environmental pressure.

The PTB indicator increased by 85.5% from 2.7 million tonnes to 5 million tonnes over the whole monitored period 2014-2019. The largest increase was recorded between 2014 and 2015 when PTB more than doubled from 2.7 million tonnes to 7 million tonnes, while it fluctuated in the following years. In per capita expression, PTB ranged from 257 kilograms to 705.1 kilograms per capita (Table 6). The PTB indicator indicates whether or not there are shifts of environmental pressure from the Czech Republic abroad and vice versa. It is possible to assume from the positive values that there was a net export of environmental pressure (the pressure exerted by the Czech Republic abroad by import was bigger than the pressure exerted on the Czech Republic by foreign countries by their export). This fact could be controversial from the viewpoint of sustainable development. The PTB indicator further shows foreign material dependency of the Czech Republic. When PTB shows high positive values the country may encounter problems if there is a scarcity or a steep increase in prices of commodities on international markets.

Looking at the PTB material categories, fossil fuels and metal ores recorded the most positive values and mostly positive values were also recorded for other unspecified products (they only showed a negative value in 2014). These commodities have to be imported, because their sources are either insufficient in the Czech Republic or their mining is not profitable. PTB of fossil fuels and metal ores grew by 38.8% and 2.9%, respectively, while PTB of other unspecified products increased from negative value of -44.6 thousand tonnes to 539.8 thousand tonnes in 2014-2019. On the other hand PTB of biomass recorded significantly negative values, which further decreased by 22.6% in the monitored period. Physical trade balance was negative also for non-metallic minerals and for waste in 2014.

DMI and DMC are internally inconsistent indicators, as one of their parts – used domestic extraction – is accounted for in terms of raw materials while physical imports and exports are accounted for in terms of products. It can therefore happen that a country decreases its material consumption measured by DMI and DMC by ceasing manufacturing of some products from domestic raw materials and importing them from abroad. It can be allowed by the fact that the weight of raw materials, which needs to be extracted for manufacturing and which is accounted for under used domestic extraction, is always higher than the weight of manufactured products, which are parts of physical imports and exports. This is true because a part of extracted raw materials is transformed into waste flows already during manufacturing and a part is used for covering energy needs of manufacturing. In order to overcome these distortions in measuring material consumption new indicators have currently been under development, which include imported and exported products in terms of all raw materials needed for their manufacturing, i.e. in terms of raw material equivalents (RME). These indicators are called Raw Material Input (RMI), which is calculated as a sum of used domestic extraction, and raw material equivalents of imports and Raw Material Consumption (RMC), which is calculated as used domestic extraction plus raw material equivalents of imports minus raw material equivalents of exports. RMC is also called Material Footprint (MF) and belongs to the same group of indicators as Carbon Footprint (CF) and Ecological Footprint (EF). RME of imports and exports can be used also for calculation of physical trade balance and evaluation of shifts of environmental pressures between countries, which is more precise than using PTB based on simple weight of imports and exports.

Methodology of calculation of raw material equivalents of imports and exports has still been under development by various international institutions and research organizations. Eurostat is currently the most advanced as regards implementation of the standardized approach for calculation, as it has been involved in this kind of research since 2009. Eurostat developed a model calculating RME, RMI and RMC for the European Union as a whole. It also developed a country tool based on this model, which allows for an estimation of raw material equivalents for particular EU countries. This is the reason why, in 2018, Eurostat could include data entries on physical imports and exports in terms of RME into a questionnaire by which it collects data on material flows from EU countries. This part of the questionnaire, however, is voluntary for the time being. Details on the Eurostat RME project, material consumption in the EU in terms of RME and about the country tool can be found at https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Material_flow_accounts_statistics_-_material_footprints#Accounting_for_trade_flows_in_terms_of_raw_materials_equivalents.

Calculation of raw material equivalents for the Czech Republic is carried out by Charles University Environment Centre in its research projects. The results show that raw material equivalents of imports and exports, respectively, are more than 3 times higher in the Czech Republic compared to the simple weight of imported/exported commodities. The largest part of raw material equivalents of imports was composed of metal ores in 2018 while raw material equivalents of exports were dominated by non-metallic minerals in this year. The second position was held by fossil fuels followed by non-metallic minerals for raw material equivalents of imports and by fossil fuels followed by metal ores for raw material equivalents of exports. The smallest part of raw material equivalents of both imports and exports was composed of biomass. Due to increase in weight of raw material equivalents of imports compared to simple weight of imports RMI indicator was by more than 73% higher compared to DMI indicator. On the other hand RMC was only by about 10% higher compared to DMC, as similar increase in raw material equivalents of imports and exports was cancelled out during the calculation of RMC.

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