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Article

Resource Use in the Production and Consumption System—The MIPS Approach

Christa Liedtke [1,2], Katrin Bienge [1,*], Klaus Wiesen [1], Jens Teubler [1], Kathrin Greiff [1], Michael Lettenmeier [1,3] and Holger Rohn [1,4]

[1] Research Group Sustainable Production and Consumption, Wuppertal Institute for Climate, Environment and Energy GmbH, P.O. Box 10 04 80, Wuppertal 42004, Germany; E-Mails: christa.liedtke@wupperinst.org (C.L.); klaus.wiesen@wupperinst.org (K.W.); jens.teubler@wupperinst.org (J.T.); kathrin.greiff@wupperinst.org (K.G.)

[2] Design Faculty, Folkwang University of the Arts, Klemensborn 39, 45239 Essen, Germany

[3] Department of Design, Aalto University, Hämeentie 135 C, 00760 Helsinki, Finland; E-Mail: michael@d-mat.fi

[4] Faktor 10-Institut für nachhaltiges Wirtschaften gemeinnützige GmbH, Alte Bahnhofstraße 13, 61169 Friedberg, Germany; E-Mail: Holger.rohn@f10-institut.org

* Author to whom correspondence should be addressed; E-Mail: katrin.bienge@wupperinst.org; Tel.: +49-202-2492-191; Fax: +49-202-2492-138.

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Abstract: The concept Material Input per Service Unit (MIPS) was developed 20 years ago as a measure for the overall natural resource use of products and services. The material intensity analysis is used to calculate the material footprint of any economic activities in production and consumption. Environmental assessment has developed extensive databases for life cycle inventories, which can additionally be adopted for material intensity analysis. Based on practical experience in measuring material footprints on the micro level, this paper presents the current state of research and methodology development: it shows the international discussions on the importance of accounting methodologies to measure progress in resource efficiency. The MIPS approach is presented and its micro level application for assessing value chains, supporting business management, and operationalizing sustainability strategies is discussed. Linkages to output-oriented Life Cycle Assessment as well as to Material Flow Analysis (MFA) at the macro level are pointed out. Finally we come to the conclusion that the MIPS approach provides relevant knowledge on resource and energy input at the micro level for fact-based decision-making in science, policy, business, and consumption.

Keywords: MIPS (Material Input per Service Unit); resource consumption; natural resources; Material Intensity Analysis; dematerialization; Material Footprint, micro economy; value chain; sustainable production and consumption (SCP)

1. Introduction

In 2013, the concept of sustainability celebrated its 300th anniversary [1]. In the last decades sustainability has become an international acknowledged principle and many governments and (inter)national institutions have implemented related programs and initiatives worldwide [2,3]. During the last 20 years resource intensity of production and consumption patterns gained specific political and scientific attention in discussing increased resource productivity as a key element of sustainable development and especially for reducing environmental impact, e.g., [4–10]. In particular, Dematerialisation is seen as a strategy to decouple natural resource use from economic growth [6,11–17]. The term natural resources refers to extraction and harvest of biotic and abiotic raw materials as well as the use of water, air and soil. The latest reviews of the global resource use show that the global economy not only needs a relative decoupling (increased economic wealth with less resources) but also an absolute decoupling (reduced resource use in absolute terms) and impact decoupling (reducing environmental impact of economic including consumption activities) [18–20].

Implemented resource efficiency indicators refer to resource productivity of countries and sectors (macro level) and rely on the availability of established methods and available datasets [21,22]. In general, material productivity (GDP/DMI) measures economic performance (GDP) and the direct Material Input (DMI) of a country. It allows us to monitor the created economic wealth (including exports) out of certain amounts of utilized materials (per time), but does not integrate knowledge on indirect material flows of unused extraction, reflected by the resource productivity (GDP/TMR) and the Total Material Requirement (TMR), see [18,23–26]. The indicators Domestic Material Consumption (DMC) and Total Material Consumption (TMC) on the other hand, quantify the consumption site of used and hidden material flows within countries (without exports) [25].

There are huge differences between countries when comparing their direct material use per capita and their overall resource use. If one compares the direct resource use for production and consumption (DMI) of, e.g., Germany (20.5 t/cap in 2008) [25], USA (24.4 t/cap in 1994) [27], and China (16.6 t/cap in 2008) [27] with their total material requirement (TMR) the resource use is much higher: Germany 73.3 t/cap (in 2008) [25] or, USA 71.4 t/cap (in 1994) [27], and China 42.9 t/cap (in 2008) [27] (see further data [28,29]). In addition, there is also a major gap between countries in terms of their extraction of natural resources. For example, current calculations of the direct domestic resource extraction (DME) of countries show a difference between about 1 t/cap (e.g., Haiti) and 139 t/cap (Qatar) [30]. The global annual economically used raw material extraction was between 47 and 59 billion metric tonnes in 2005. It has been increased by factor eight during the last century (between 1900 and 2005) while the global population only increased by factor four [20]. Krausmann *et al.* [31]

and Wiedmann *et al.* [30] showed a further increase of global material extraction until 2008 up to 67 to 70 Gt. The concept of "Factor 10", which was first presented by Friedrich Schmidt-Bleek in the early nineties [6], sets the goal of a tenfold decrease of natural resource consumption in Western countries by 2050 to reach a sustainable level of global resource consumption [4,25,32–37].

Also, international initiatives such as UNEP launched a specific program and framework on resource use and sustainable consumption and production (SCP) [38]. Ever since, reducing material and energy intensity have been key principles of international actions towards SCP [2,3]. Especially European policy processes aim at increasing resource productivity [39–43] addressing raw materials, energy, water, air, land and soil. The EU discuss—beyond measuring DMC—an extended resource use indicator such as total material consumption (TMC) [44] and has suggested a complementary indicator set ("dashboard") in the categories land, water and carbon [45]. Towards resource efficient production the milestone has been defined, that by 2020 "*Economic growth and wellbeing is decoupled from resource inputs and come primarily from increases in the value of products and associated services*" [43] (p. 6).

Although a clear vision and overall goals are given, the accounting methodologies to measure a decoupling of resource inputs from well-being and economic growth in the production and consumption system are still under development. The related assessment requires adequate indicators for monitoring and reporting on all levels of economic activity [42,46–48] (pp. 5–6). There is also a need for a reliable indicator (set) and database providing aggregated data on resource intensity at micro and meso level. In this paper the concept of MIPS (Material Input Per Service unit) is illustrated as such a method to measure the resource intensity of production and consumption patterns and can be applied for decision-making in companies and households towards a low resource society and economy [9,36].

The MIPS concept has been developed to provide a proxy for ecological measures [6] (p. 101). It takes into account the multi level effects between the micro, meso and macro level of economy [6,7,49] and can be applied to management processes on the micro level as it is a reliable measure for their impacts. The methodology to calculate MIPS is the Material Intensity Analysis (MAIA) [50].

This paper reflects the current state of research and methodology of MAIA at micro and meso level. The term meso level refers in this paper to the level of companies, but to the level of branches. For the application of MAIA or related methods at macro level see, e.g., [49,51]. The paper aims at presenting an overview of the assessment method at micro and meso level as basis for:

- Discussion of several application fields of calculating material intensity mainly developed in German/European research projects;
- Discussion of current challenges and open questions of MAIA method;
- Discussion of future research needs;
- Finally, provide an updated basis for further discussion of the MIPS concept and MAIA method with an international scientific community of environmental assessment.

Embedded in a brief introduction of the MIPS concept the authors present its basic principles of input and service orientation as well as its main calculation steps as a summary of MIPS research to enhance the understanding of application discussion for the reader including examples of MIPS results (Section 2). After that, the authors present the generic micro and meso level application of MIPS for assessing value chains, supporting business management, and operationalization of sustainability strategies, which have been developed and tested in research projects or represent future application fields (Section 3). Finally, we come to the conclusion that the MIPS approach provides relevant knowledge on resource and energy input at the micro level for informed decisions of science, policy, business, and consumers (Section 4).

The paper does not thoroughly discuss the existing MIPS database itself. However, the given examples in the paper emphasise the presented research results or discussion questions. The authors invite the reader to comment on the MIPS concept and MAIA method.

2. MIPS Concept and Methodology

The MIPS concept was established around 20 years ago. It was introduced by Friedrich Schmidt-Bleek in 1992 in order to operationalize the concept of dematerialisation and its management on economic micro, meso and macro level (first published in 1993 in [6,52]). It is based on the idea of the "ecological backpack", which is a metaphor for the burden of natural resources every object "carries" in addition to the materials it contains directly. MIPS results can be used to downscale the Factor 10 concept into a metric and tangible unit for technologies, products, processes, services, and systems (e.g., companies [12,53–55] and households [36,56]). Macro level assessment of economies and sectors are not further discussed in this paper (see specific publications, e.g., [28–30,57,58].

The basic principles of the MIPS approach include input (Section 2.1) and service orientation (Section 2.4). In the following, we discuss these two principles and present the MIPS calculation based on MAIA. Additionally, the authors discuss major interlinkages of the MIPS calculation and the sustainability strategies efficiency, consistency, and sufficiency.

2.1. Principle of Input Orientation: Prevention Indicator

The MIPS concept is based on the fact that inputs in the human production and consumption system (technosphere) are finally converted into outputs with environmental impacts, e.g., climate change, eutrophication and acidification. Consequently, resources (material inputs incl. those for energy) taken from nature (ecosphere) lead to an increase of outputs (e.g., emissions, waste) and potential impacts. MIPS considers all moved primary material in nature connected with known and yet unknown impact to the ecological system.

The input focus of MIPS follows the idea of the matter-energy conservation law assuming quantitative equivalent inputs and outputs. Accounting input material flows allows preliminary estimation of the environmental impact potential of products and services [6,9,33,49]. Thus, MIPS is a practical solution to reduce the complexity of the assessment as well as the uncertainties that go along with output-oriented assessments such as the ISO 14040/44 LCA [59,60]. Many emissions last for decades or even centuries in the ecosphere, impeding the assessment of future impacts. In addition, it can be assumed that still only a small amount of all potential environmental toxins, their interactions and the resulting impact on humans and nature are known. And even if effects are known, it can take many decades until their elimination. Lead, for instance, (since 1978 lead pipes are banned in new buildings in Germany due to harmful effects of bio accumulation/lead poisoning) and the insecticide DDT (20 years after first hints of harmful effects in the 1950s it was banned in the 1970s in the USA, Canada, and Europe, resulting in the international Stockholm Convention in 2004: however, it is still in use for disease vector control) [61,62]. This example shows that there can be a very long period from the identification of impacts to the realisation of measures to avoid them. Processes to analyse such impacts are necessary but not sufficient for precautionary protection of the environment. For this, reducing the material flows on the input side will help to avoid and minimize outputs and thus known and unknown negative impacts. In addition, known toxic substances can be directly avoided or minimized at the input side respecting the legally defined limits and following a more holistic resource management understanding [7,33–35]. MIPS is not developed to quantify specific outputs (e.g., emissions of specific toxic substances) and assess their impacts (e.g., acidification, GHG), but supports an optimized resource input management [63,64]. Besides, the input-oriented MIPS concept is mostly compatible to an output-oriented LCA. If a MIPS analysis or other material and substance information indicate the need for deeper analysis of different indicators or impact categories, they can be assessed simultaneously or afterwards [32].

2.2. MIPS Calculation

The MIPS calculation has been described in [6,34,50,52]. This chapter summarizes the basic calculation convention. MIPS implements the demand for quantifying the resource use of technologies, products, processes, services, and systems (e.g., companies, households, regions, *etc.*).

$$MIPS = \frac{MI}{S} = \frac{Material\ Input}{Service\ unit} \tag{1}$$

The formula describes how much primary material—or actually "nature"—is being removed for the production of a product or the provision of a service (S). The term material comprises all required natural resources. Resources themselves are defined as raw materials including such for energy carriers and transports. The reciprocal of MIPS (S/MI) describes the resource productivity, which means the amount of service provided by a certain amount of natural resources [34,50].

The unit for the material input is kg or tonnes. When related to material, energy or distance, it is also called material intensity, e.g., kg/kg steel, t/MWh electricity; t/km transport, encompassing infrastructure (e.g., streets, buildings, harbours, *etc.*) as well as transport carriers (e.g., trucks, trains, *etc.*) and their energy consumption (e.g., fuels, electricity, *etc.*) [50,63,65]. The service unit has no fixed dimension. It has to be defined in accordance to the specified delivered service, e.g., for transport (transportation from A to B with different vehicles calculated as person kilometres or tonne kilometres), clean clothes (e.g., wearable T-Shirt for one year) or nutrition and meals (e.g., kcal per portion) [36,50,63,66,67].

The MIPS concept measures natural resource use throughout the entire life cycle (resource extraction, manufacturing, transport, packaging, operating, re-use, re-cycling, and re-manufacturing, final waste disposal) of technologies, products, processes, and services. This can be done on a product and company level. MIPS takes into account direct and indirect material use as well as used and unused extraction [6,7,33,34,49,63]. The latter is particularly important, *i.e.*, that the material input includes both resources used in human economy and unused extraction [23,26,68]. Thus, all material flows caused by humans are calculated irrespective of their economic benefits.

MIPS measures removed resources in up to five natural resource categories: abiotic raw material, biotic raw material, water, air, and earth movements in agriculture and forestry (erosion, mechanical earth movement) [50]. Raw materials include metallic and non-metallic minerals (ores, rocks, sand, *etc.*), fossil energy carriers (such as coal, mineral oil, natural gas). Energy and transport is calculated by the sum of all raw materials necessary for its production, including the required infrastructure [50] (p. 98). The different categories can be disaggregated in different materials and its life cycle use, if necessary, so that the amount of each material or substance is transparent and therefore useful for decision-making processes in environmental and sustainable management processes (e.g., [13,69]).

A MIPS calculation can be performed using primary data for a specific case. However, it becomes more feasible by using pre-calculated coefficients representing the average material intensity of, e.g., basic materials, chemicals or agricultural products. This helps to avoid the calculation out of primary data each time, which would require complex and labour-intensive calculations. These average material intensities give the average amount of natural resources in the above-described five categories used to produce a certain amount of material (e.g., 1 kg copper or polyester). The most comprehensive list of MIT factors is published by the Wuppertal Institute [70]. The list is continuously updated.

$$\mathrm{MIPS}(x) = \frac{\sum_{i=0}^{\mathrm{n}} \mathrm{m}_i \times \mathrm{MI}_i}{\mathrm{Use}(x)} \tag{2}$$

The formula shows the principle calculation: MIPS is calculated by multiplying the inputs (e.g., masses, energy carriers) by their material intensity (MIT factors) and summing up all results per MIPS category. Where x is the product/service, MIPS (x) the MIPS result of x, m_i amount of input i, n number of inputs, MI_i material intensity of input i, Use (x) service of product x [6,50,71,72]. Dividing these sums by the defined service unit (S) gives the MIPS result (see Table 1).

MIPS analyses using MIT factors can be easily done using common spread sheet programs or even pen and paper. However it has the disadvantage that modeling complex systems is very time consuming. Also the graphical analysis or complex sensitivity analysis (e.g., using Monte Carlo models) can get very extensive. In [73], the authors describe how to calculate MIPS using LCA software and matrix inversion, which opens up possibilities for enhancing MIPS-models. Another advantage of this approach is that data from LCA databases can be used. However, there are currently many challenges left which are described in [74].

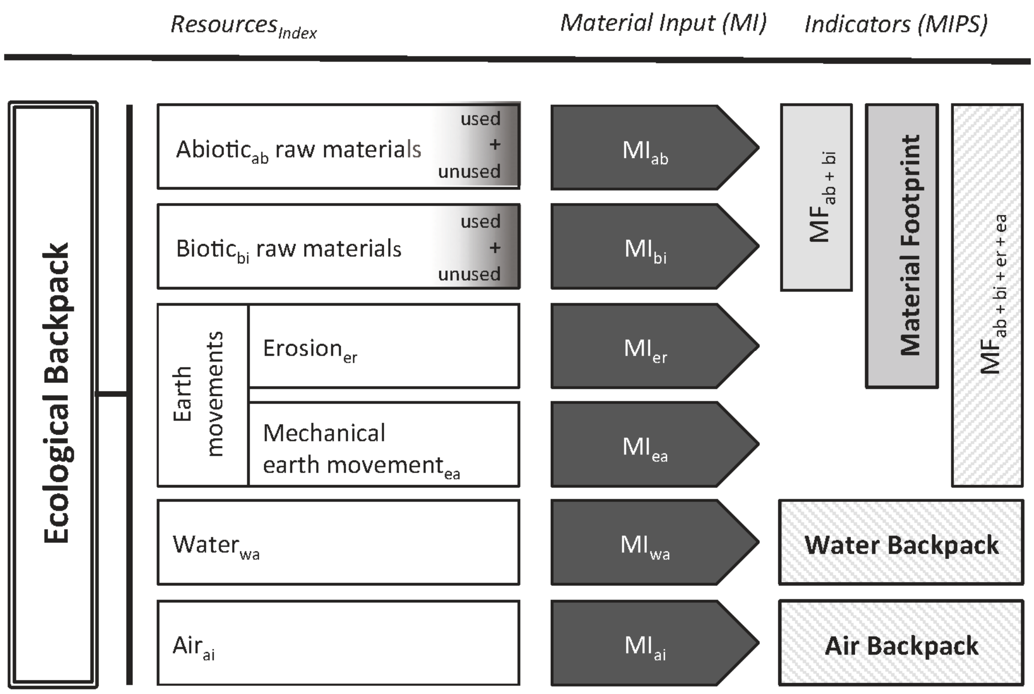
2.3. MIPS, Material Footprint and Ecological Backpack

In principal the five MIPS resource categories are calculated separately. In total they are known as the Ecological Backpack. The resource categories can be used for a subset of indicators. They are illustrated in Figure 1, which shows the five resource categories: abiotic, biotic, erosion/earth movement, water, and air. First there is the *Material Footprint*, which was established in 2009 by Lettenmeier *et al.* [63] as a parallel term for the ecological backpack created by Schmidt-Bleek [6]. The Material Footprint (MF) has been applied in projects such as [56,75]. Although the term footprint is originally closer related to land use aspects (the ecological footprint that was launched first [76,77]), the acceptance of the "footprint family" not only focusing on land use (e.g., carbon footprint, water footprint) is broad, e.g., [78,79]. The Material Footprint aims at completing this "family" as an indicator focusing on material resources ($MF_{ab+bi+er}$). It can alternatively focus on abiotic and biotic resources, in case data on earth movements are not available (MF_{ab+bi}). Further indicators are the Water Backpack and the Air Backpack, which reflect the resource categories water and air.

Table 1. Material Intensity Analysis (MAIA) calculation sheet with exemplary calculation principle for abiotic raw materials.

partial process 1 up to partial process n			**Abiotic (ab)**		**Biotic (bi)**		**Earth movement (ea)/erosion (er)**		**Water (wa)**		**Air (ai)**	
substance /pre-product	amount	unit	MIT factor kg/unit	kg/unit main product	MIT factor kg/unit	kg/unit main product	MIT factor kg/unit	kg/unit main product	MIT factor kg/unit	kg/unit main product	MIT factor kg/unit	kg/unit main product
[name] 1	m_1		MI_1	$m_1 \times MI_1$	...	...	...	...	...	...	...	...
[name] 2	m_2		MI_2	$m_2 \times MI_2$	...	...	...	...	...	...	...	...
[name] 3	m_3		MI_3	$m_3 \times MI_3$	...	...	...	...	...	...	...	...
...	...		...	...	...	...	...	...	...	...	...	...
[name n]	m_n		MI_n	$m_n \times MI_n$	...	...	...	...	...	...	...	...
∑ partial process 1				$\sum m_i \times MI_i$		$\sum m_i \times MI_i$	...	$\sum m_i \times MI_i$		$\sum m_i \times MI_i$		$\sum m_i \times MI_i$
(...) calculation of further partial processes (e.g., life cycle stages)			...	...	...	...	...	...	...	...	...	...
∑ MI (sum of all partial processes)				MI ab		MI bi		MI er MI ea		MI wa		MI ai
Total amount of service units												
MIPS (MI per one service)				MIPS ab		MIPS bi		MIPS er MIPS ea		MIPS wa		MIPS ai

Figure 1. Resource categories, Material Input (MI), and Material Footprint (MF).



Regarding its resource categories, the Material Footprint equals the macro indicator Total Material Requirement (TMR), which can be used to measure the physical metabolism of national economies (including used and unused extraction as well as indirect flows, see [23]) [22,68]. As the TMR considers exports of an economy, the Total Material Consumption (TMC), which excludes exports and the related indirect flows, is a suitable measure for comparison, when results from a MIPS analysis related with consumption, e.g., of households, are scaled up to macro level.

In general one can say that MIPS supports analysing and finding the best possible way of reducing and preventing resource extraction from nature, *i.e.*, reducing the material input and thus environmental impact, while increasing the service at the same time. Although the MIPS concept allows weighting of resource categories usually each resource category is calculated separately (unweighted). The results of a MIPS analysis can be used for resource management addressing the environmental media soil, water, and air [32]. Finding the best alternative the weighing of results and categories might be useful and have to be discussed with stakeholders: depending, e.g., on regional water situation it can be reasonable to weigh MF_{wa} higher than MF_{ab+bi} [63,72].

2.4. Principle: Service Approach

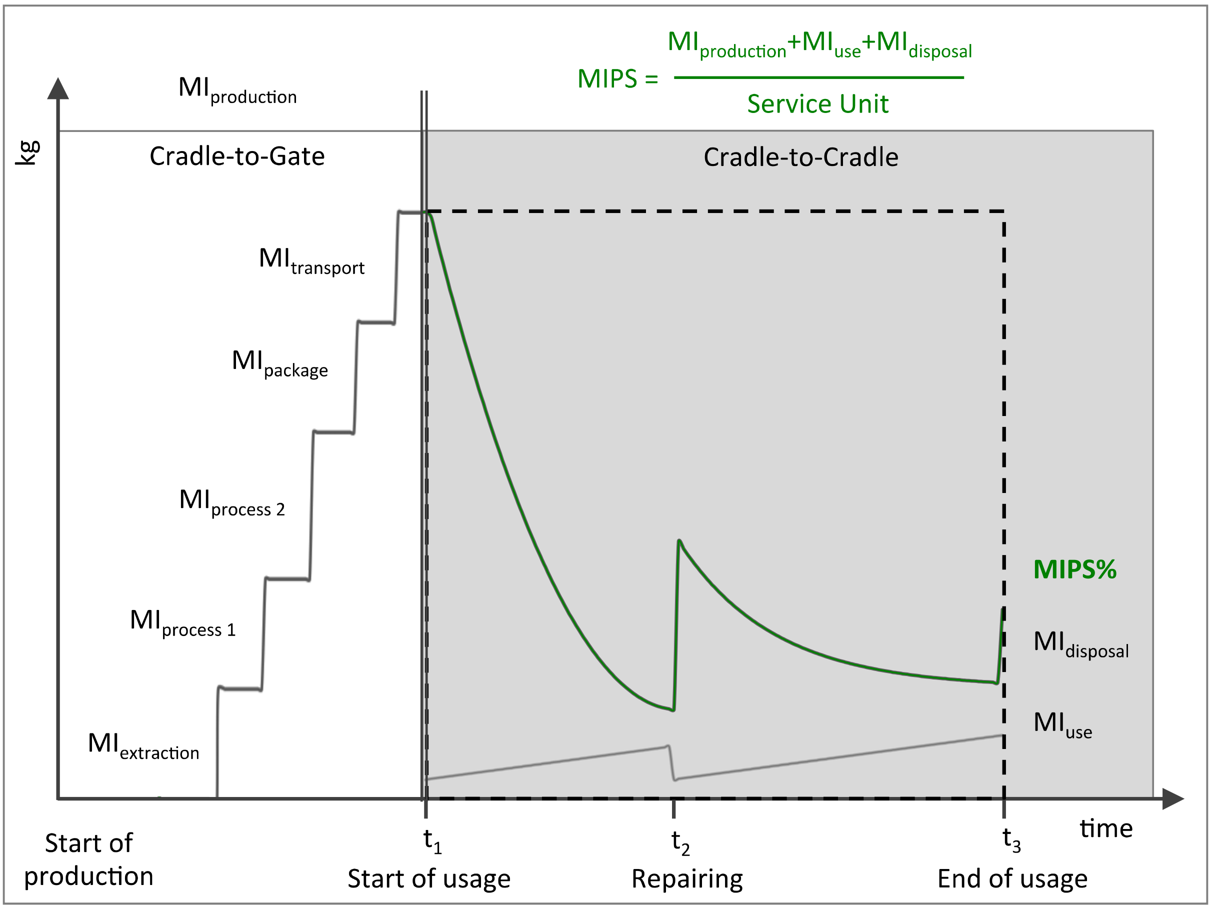
The concept of service (S) in MIPS (MI/S) is based on the notion that any product provides a specific service or fulfils a specific need [6,50]. In this sense MIPS compares not only products, *etc.*, but also services or needs that can usually be fulfilled in different ways. Depending on the product analysed, one service unit can be expressed in utilization (comfortable transfer from A to B, hygienic and clean, on my skin pleasantly portable and fashionable, my lifestyle underlining and expressing clothing, *etc.*) related to a period of utilization (e.g., 1 year, 1 day reflecting longevity, reusability, repairability). For the specific assessment the service bundle will be described respecting the individual and social needs (e.g., identity, relatedness, competence, security, self-determination [15,80] and for calculating a quantified measure related to a service unit (e.g., good life in my home environment: which amount of resources per chosen product mix and m^2 and year or an average life time per flat is consumed?) [14,50]. In the broader sense MIPS is asking the question about quality of life or personal meaning [15,80,81], because quality of life is not determined only by the consumption of goods [15,82]. Hence, in addition to optimizing just a specific product or service, the MIPS concept directly leads to the consideration of how the desired service can be fulfilled in the most resource efficient way [14,83].

As a life cycle wide approach, MIPS has linkages with the LCA framework [59,60] regarding the definition of system borders and service unit of a product system. The service unit of the MIPS concept equates in many cases to the functional unit of the LCA. However, it refers to the provided product service and therefore allows a wider and more holistic approach [14,15].

Figure 2 schematically shows this general assumption displaying time on the x-axis against mass unit (e.g., kg) on the y-axis. On the left, the cradle-to-gate assessment accumulates the material input of production phase (including resource extraction, several processes, package, and transport). The MI is growing until start of usage (t_1). On the right, the cradle-to-cradle assessment illustrates MIPS, which equals the sum of $MI_{production} + MI_{use} + MI_{disposal}$ per Service Unit at a specific assumed life time.

The green graph shows that with a growing amount of services and a given MI, the MI/S (MIPS) diminishes. At point of repairing (t_2) MIPS increases due to necessary input but decreases due to prolonged life time (t_3). The grey graph illustrates MI_{use}. The longer the use phase the more MI is consumed (e.g., energy use). Repairing not only prolongs the life time but also reduces MI. MIPS calculation also includes the MI of disposal. It is obvious that a product's second life (e.g., re-use, upcycling, sharing, cascading) is only reasonable if the MI for recycling or similar processes is not higher than for primary production, which would not be reasonable in terms of a limited environmental space [6,7,14,36].

Figure 2. Schematic Material Input per Service Unit (MIPS) calculation (adapted from [6]).



3. MIPS Application Fields at Micro and Meso Level

Due to the increased complexity and globalization of production processes in value chains, the demand for management and controlling strategies is changing. Actors who deal with product chains, such as entrepreneurs, politicians and retailers, need to manage an increased complexity in order to monitor all on-going processes with the objective of optimizing value chains in terms of resource use [84–86]. Beside this they have to reflect a complex socioeconomic indicator set and standards (e.g., SA 6000, ISO 9000, ISO 26000, Reporting systems, *etc.*) to manage their companies and value chains from resource extraction to recycling processes. Decision making on the micro level needs a more holistic view on different system wide management criteria to improve and optimize the processes with a high responsibility for economic, social and ecological challenges [19,45,48]. For instance, resource efficiency is an increasingly integrated aspect in the production system: Companies define their goals and strategies including resource use indicators. Some already use MIPS as an indicator for their resource management. Others focus on selected resource use aspects (e.g., direct energy use, waste, CO_2 emissions) [54]. In the following chapter we present generic micro and meso level application of MIPS, which have been developed and tested in research projects or represent future application fields. The MAIA can be applied on several levels (value chain, life cycle, product, company, household, economic sector, regional or national economy) and is able to provide results for different levels of application.

3.1. MIPS Application along the Value Chain

Table 2 gives an overview of current examples of MIPS application along the value chain including business management. The applications have been or are being developed and tested in various research projects. Future options are also given to show extended application fields. Production aspects that have been analysed in research projects are reflecting the MI of single processes and life cycle phases or segments of value chains, e.g., cradle-to-gate or gate-to-cradle assessments. Gate-to-Gate assessments have been focusing on the production site. Also products and services, business models, the construction and maintenance of infrastructures, energy and transport have been assessed. Business perspectives (company, processes, products) are relevant focusing on the relationship between MAIA and monetary units used in business management (e.g., costs). The aim is expressing the use of natural resources at company level to inform economic actors on environmentally relevant information based on their existing business, eco accounting processes and indicators [54]. Another MIPS application has been developed for household level to record and assess resource use of private households reflecting an important level of the consumption patterns assessable by MIPS [36,87].

3.2. MIPS Application towards Integration of Sustainability Strategies

The MIPS concept helps to approach the assessment of the sustainability strategies of efficiency [6,88,89], consistency [6,90], and sufficiency [6,91,92]. Whereas efficiency describes the idea of producing *better* (less resource and energy input per service), the consistency strategy aims at producing *differently* (closing loops, change composition or quality of resource and energy input). Finally sufficiency is about producing and consuming *less* (enhance welfare with decreasing resource demand). Those sustainability strategies complete each other [14]. Together they contribute to reducing the MI and increasing the S. The integrated consideration of these sustainability strategies along with further strategies (e.g., deceleration of consuming goods [93]) aims at resource use reduction per capita in absolute terms [6,11,14,36,50,83,94].

Efficiency is defined as resource and energy savings per service unit either within production processes or throughout the entire life cycle. Table 3 shows resource efficiency examples of different energy supply systems. Offshore wind energy is the most efficient system when compared to biogas plants and lignite-fired power plants. On the basis of this kind of comparison, the development of transition paths towards increased resource efficiency is possible.

Table 2. Examples of MIPS application along the value chain.

	MIPS application: Current examples (selection) and *future application (own suggestion)*	References of current examples (selection)
Production	**MI Processes and life cycle phases**: Single processes up to life cycle phase (e.g., extraction, production, use, recycling), *R&D of processes*	[66,69,94–101]
	MI Value chain: Cradle to Gate, Cradle to Grave/Cradle, Gate to Grave/Cradle, comparison of value chains and life cycle phases, material selection/design, *R&D of technologies/products (including development, prototyping, testing, roll out), R&D of services*	[66,69,95–97,100,102]
	MI Production site: Gate to Gate, multinational companies, small and medium sized enterprises, *cluster, industrial symbiosis*	[12,13,53,103,104]
	MI Products & services: Single products, product bunch for services, *comparison of product & service bundles*	[13–15,69,94,96,102,103,105]
	MI Business models: Service concepts, *concepts for logistics/distribution/diffusion*	[12,13,15,53,54,99, 101,102,106,107]
	MI Infrastructure: Construction & maintenance of infrastructure	[69,96,100,108–110]
	MI Energy: Power stations, energy source/storage, electricity/heat supply	[69,71,100,110]
	MI Transport: Mode of transport, mobility, *logistics, fleet management*	[50,69,111]
	MI Closed loops: at the production site, *between process chains, closed loops in whole value chains, between sectors, micro and meso level*	[12,54,66,67,100–102,112]
	MI Critical resources: Share of critical resources in total MI, *integration of material input into assessment of critical resources*	[113,114]
Consumption	**MI Consumption**: Households, individuals, groups (e.g., singles, families, age, profession), *social milieus,* companies, *public institutions, city district, region*	[66,111,115–117]
	MI Needs: Housing, mobility, nutrition, tourism, clothing, leisure time, health, *education, participation*	[66,67,75,111,112,118,119]
	MI Social practices: *Routines, action patterns (of production, consumption, production/consumption)*	[105,120,121]
	MI Rebound effects: *Shifting between areas of need, products, services, direct and indirect rebound effects*	[14,15,114]
	MI Use (including management): Operate, maintain, repair, re-use, re-manufacture; *leasing, contracting, sharing, cooperative use concepts, Do it Yourself*	[15,67,75,94,106,116,117]
Balance	**Material flow balances**: MAIA is applicable on several levels (product, small company or, e.g., the material footprint of multinationals, economic sector, local, regional or national economy)	[12,56,101,116,117,122–126]
	MI Input per Output: Resource productivity of households, companies and sites	[12,101,114,121–126]
Business management	**MI company in relation to their added value**: time series, comparison between branches	[12,54,101,122,127,128]
	Sales per working place or MI per working place: e.g., sales and resource use in large-scale enterprises per region and business unit; comparison between branches	[54,114,126]
	MI of process costs or production costs: at process level: identification of high ecological and economic "cost drivers"; comparison of similar processes within branch; at product level: time series, knowledge base for product portfolio management	[54,55,114,127]
	MI resource accounting: Resource cost accounting, direct material (costs), costs for processing/disposal burden/overhead materials	[54,55,114,127]
	MI Price: Method and indicator base for calculation of "ecological appropriate prices"	[54,114,127,129]

Consistency describes the strategy of closing ecological loops within processes (parts of process chains), at production sites (e.g., by returning waste or discards into processes) or throughout the entire life cycle (e.g., by designing completely recyclable or degradable materials and products) provided that the material input for closing loops is not higher than for primary production. Thus, consistency and efficiency support sufficient consumption patterns with consistently and efficiently designed products and services [15,83,94]. Table 4 shows an example for considering consistency on the basis of the MIPS concept. Comparing both primary and secondary production of basic materials often shows the high potential of recycled or secondary material for a lower resource input per product or service.

Table 3. Resource intensity (material, water, air) of different energy supply systems [50,130].

Material Input (kg/MWh)	MF_{ab}	MF_{bi}	MF_{er}	Water Backpack	Air Backpack	$MF_{ab+bi+er}$
Offshore wind energy	177	0	0	795	9	177
Biogas plant	595	2,973	346	1,747	954	3,914
Lignite-fired power plant	11,271	0	0	56,824	875	11,271

Table 4. Resource intensity (material, water, air) of primary and secondary aluminium [70].

Material Input (kg/kg)	MF_{ab}	MF_{bi}	MF_{er}	Water Backpack	Air Backpack	$MF_{ab+bi+er}$
Aluminium primary	37	0	0	1,074	10.87	37
Aluminium secondary	0.85	0	0	30.74	0.95	0.85

An additional aspect to be considered is that unused extraction—that does not end up in products at all—equals about one third of all material flows and presently is not transferred into a loop economy. Due to that and the resources embodied in the infrastructures of transport and communications systems only 3% of material flows are recycled at all [7] (p. 13). Thus, by accounting also unused extraction and hidden material flows, the MIPS concept also reflects the notion of consistency [14,50].

Sufficiency describes the orientation of performing social and individual acceptable activities within a limited environmental space [87,131]. From a Western perspective, sufficiency is probably the most challenging sustainability strategy asking "why and how needs can be met while minimising environmental damage without too much losses in quality of life" [14] (p. 7). It aims at production and consumption patterns implementing, e.g., management structures, which lead to products and services appropriate to the abovementioned orientation principle [53–55]. Thus, sufficiency is an applicable management strategy within the entire value chain [132] and addresses both production (business strategies) and consumption patterns. Studies concerning the material footprint of households show us a factor 9 difference between different households (13 to 120 tones per capita and year [133]) or a 113% difference from average energy use for heating per m^2 capita and heating period in the same multifamily house [134]. Material footprints of selected consumption areas, e.g., 10 km bike-riding (1.3 kg) and 10 km car driving (11.3 kg) or eating a vegetarian burger (6.45 kg/kg meal) and eating a double burger (28.80 kg/kg meal) show their material efficiency potential of different choices (own database [133]).

Table 5 gives examples of MIPS application aspects that either support single sustainability strategies or provide an integrated perspective of all three strategies efficiency, sufficiency, and consistency.

Table 5. MIPS application towards integration of sustainability strategies and resource use targets.

MIPS application aspect		Application examples (selection)	References of current examples (selection)
Efficiency	Used/unused resources	Value chain perspective: proportion of used and unused resources over life cycle	[12–15,49,51,54,55,66,69, 71,101,113,116,117,130]
	Unused resources/profit Used resources/profit	Company level: proportion of unused resources and profit	
Consistency	Unused/product weight MI/product weight	Assessment of recycling strategies at different levels: location, process chains, value chain, between sectors, micro and meso level	[14,15,69]
	Unused resources/ production costs	Assessment of recycling strategies, closed loops, costs of unused resources processed during the life cycle or per production site	[14,15,69]
Sufficiency	MI individual resource use/resource target	Assessment of current resource use against resource targets or of earlier resource use against reduced resource use	[36,135]
	Well-being/MI	Experienced well being per household inventory, time, activities	[14,15,75,135]
	MI/time	Deceleration/slowdown in different areas of need/activity fields	[12,14,15,135]
	MI/S	Resource input per service aiming at high service and low material input	[14,15,75,91,92,101,132]
	MI/land use of activities	Land use of activities, e.g., living, working; specific inventories of products, materials, raw materials, clearing out	[9,24,25,37,136]
Targets	MI targets MI present resource use/MI target	Political targets and sustainable limits at city/regional, company or household level	[36,124,125,131,137,138]

The MIPS concept is useful for developing production and consumption patterns that are in line with the environmental space we have [36,87]. Resource targets have been suggested, e.g., by Lettenmeier *et al.* [36,75] for the household level. While this is a beginning debate about globally acceptable economy-wide resource use levels and household inventories, it is an important link between political discussion and the public debate about common sustainability strategies.

4. Discussions and Conclusions

This paper provides a concept and method for an indicator, which is able to measure resource input into the production and consumption system life-cycle-wide and for different subsystems (e.g., life cycle phases, processes, production sites, transports, energy use, *etc.*). It focuses on the movement of natural resources from nature into the technosphere. Thus, it complements the previously dominant output orientation to the aspect of resource extraction and resource management through the economic system.

4.1. Political Key Strategy: Resource Efficiency

Production and consumption patterns of industrialised countries are linked to an extensive resource use. This leads to substantial damage to the environment and climate [6,7,9,35,131]. A comprehensive resource efficiency and dematerialisation policy is necessary to address the drivers and barriers for transformation pathways towards a low resource economy and society. Thus, intelligent mixed policy instruments can empower actors located in a multi-governance system to decide commonly towards resource efficiency and conservation, to accept a resource saving cultural orientation and to implement more system-oriented resource management options [42,43,139–142]. Meyer shows using his Panta Rhei Model that there are high potentials for state budget, employment development, innovation activity and resource efficiency, if an adapted policy mix will be implemented [143]. Further organizations surrounding material efficiency, e.g., in Germany the Effizienz-Agentur NRW (EFA) (translated: North Rhine Westphalia Efficiency Agency, founded 1998), the German Material Efficiency Agency—demea (founded 2005) or VDI Centre for Resource Efficiency (founded 2009) show such impacts aiming at knowledge transfer, awareness raising, developing and providing tools, and supporting enterprises and households by identifying and exploiting their resource and material efficiency potentials (see list of German initiatives in [48]). In Germany, e.g., demea consults companies on possible improvement of their resource efficiency. Evaluations of their consulting work (550 cases) shows that in average 210,000 Euro respective 2% of annual turnover has been saved due to resource efficiency policies [144,145]. Such institutional structures will help to foster transition processes towards a resource efficient society and are a key element for successful diffusion strategies [146,147]. Successful actors and change agents want to show their resource effiency performance—this could be done with an indicator and harmonized calculation method such as MIPS.

4.2. Data Base Challenges

Today the MIPS database comprises numerous MIT Factors, which have been calculated by the Wuppertal Institute. The database is publically available and lists resource intensities of metals, basic materials, plastics, chemicals, energy and fuels, transport, construction materials, and agricultural products (relevant for different regions) [70]. The database has been constantly enhanced and revised within different research projects. Further data has been published, for instance, in Finland in the context of household consumption [133] and in Austria in different business contexts (e.g., [148]). Currently e.g., the energy data of the Wuppertal Institute database is updated [69,71,130].

Nevertheless the MIT factors differ in their quality and actuality due to complex data generation, which sometimes allow only a rough estimation. MIPS is intended to be an indicator that works with data uncertainties but is reliable in roughly estimating the current use of natural resources. The topic of data generation and quality including aspects such as transparency, documentation, actuality, allocation, and system boundaries is highly relevant in the whole field of life cycle assessment. The difficulties are not connected to one specific method such as MIPS; it is a complex topic within the whole LCA community, e.g., [149].

One reason for this is that the problems concerning a general structured process of data generation and evaluation with public availability are not yet solved. There is a need for further improvement towards an international resource intensity data centre [150–152] and tools that support enterprises and households to provide relevant information on resource intensity in their value chains and management processes (e.g., towards informed decision making, product design, portfolio management and for households also the management of the usage phase and their product-service mix). As LCA databases are the basis of LCA software, a first step should be the extension of current LCA databases towards a more complete inclusion of resource-relevant aspects. Databases like Ecoinvent (about 4000 processes) or ELCD (300–400 processes) only consider economically used resources. To achieve a compatibility with MIPS, a first step would be to integrate unused extraction (e.g., mining overburden, unused biomass) and biomass flows (economically used cultivated biomass). The core issues for a successful implementation include the introduction of elementary flows for unused extraction and the international trade of resources, see, [73,74].

Data for unused extraction have been gathered within the research project INDI-Link [153] and are being updated within the EU project CREEA [154]. However, to assure extended and regularly updated resource data, the data collection should be conducted by an external or statistical agency. Ideally an international institution, which provides technical and financial assistance, would host it, helps to coordinate and implement guidelines and standards for data provision, and insures data quality and transparency [55,147].

The management experience of all related actors involved could be an excellent starting point for a concerted action supporting a more systemic development of reliable data for estimating the environmental impacts in change processes of the SCP system.

4.3. MIPS: Methodology

In the field of material flow accounting and environmental assessment the MIPS concept is a complementing approach, especially regarding meso- and micro-level resource input assessment [155,156]. MIPS can be used in line with the EW-MFA [12,138,157]; thus, both perspectives support bridging the gap between micro- und macro-level assessments.

In addition, MIPS can complement environmental assessment by identifying rebounds effects. They are not a paradox side effect of efficiency gains but created by an increased consumption of real active consumers (and producers): on average there is a direct compensation of efficiency gains in production of up to 50% by consumption [14,158].

There is great need to assure that the measures leading to a decrease of green house gas emissions do not result in higher overall resource consumption. Examples are electric vehicles, which can contribute to a reduction of GHG emissions when using electricity from renewable energies, but might lead to an increasing of resource consumption [159].

Efforts to implement resource efficiency at company level can be seen by the development of guidelines on resource efficiency by the German Association of Engineers VDI started in 2011. The guidelines provide a framework defining resource efficiency and considerations for the producing industry. They include a special guideline for SMEs as well as guidelines on methodologies to evaluate resource use indicators such as the cumulative raw material demand of products and production systems [160]. MIPS can be used as a method to implement resource efficiency within these guidelines at the micro level.

4.4. MIPS: Application

There is an increasing demand for simple, reliable and robust accounting instruments that are based on aggregated information to show total resource efficiency potentials without being too cost or time intensive [8,34]. The MIPS concept allows a measurement to focus specific resource aspects at the production and consumption side. Within business management, MIPS can be used to achieve a resource efficiency perspective.

MIPS has been applied and further developed in multiple research projects regarding different target groups and application fields within the last 20 years. On a company level, MIPS was initially used to improve resource management of small companies [53] as well as corporations with complex value and supply chains ([69,148], see further application examples at company level [25] (pp. 23–25, 39–43). However, the implementation of resource use indicators along the value chain still needs harmonization for measuring the absolute savings and monitoring of progress, problem shift from one sector to another or one medium to another or caused unexpected rebound effects [96]. In addition harmonization is important for target definition in the economic and societies subsystems, e.g., economy-wide, in sectors or branches, in value chains, processes, for technology development, *etc.* The debate over appropriate target definitions is already performed intensively to receive guardrails for the further economic and societal development [9,25,35,36].

First experiences on the field of computer-based resource accounting could be made in the CARE project [54] while in the on-going EU funded project myEcoCost [55] a software system will be developed to inform all economic actors on environmentally relevant information (of which MIPS has been proposed as an indicator for). This perspective is valuable for companies because it is connectable to current cost accounting systems and thinking. Further, existing resource efficiency potentials are not achieved in many companies [69,141,142].

Regarding the consumption side, MIPS has been applied for the analysis of the resource use of lifestyles and households in Finland [75,133]. For Germany, first research projects focus the data collection of consumption activities within households [161,162], but extended analysis with comparable results are missing.

4.5. Future Challenges for Research

To improve measuring resource consumption on the level of companies, consumers and households (Table 2), the links of statistical classification and monitoring with companies' reporting systems and lifestyles of consumer have to be developed. Currently, statistics use an aggregated framework with limited data on socio-demographics and material inventories, which do not consider a sufficient classification of products and their use on the consumption side. Also, statistical information from companies should be improved to better serve natural resource use assessment and management.

Nowadays, the most relevant needs of households as well as the most relevant business sectors in terms of resource use are known relatively well (e.g., [36,44,133]). In order to initiate and accelerate the transition to a low resource society, further research and future assessments should have their first focus on processes, products, sectors, activities and lifestyles of high relevance and dematerialisation potential (such as living and housing, food and nutrition, mobility), also in order to better address them by environmental and economic politics. Other fields should then follow.

Even though there have been done many MIPS analyses, they are not always updated frequently or they aim at specific regions (e.g., the Finnish MIPS studies [56,133]). In addition some of the studies behind the present MIPS database, although having reached high standards, have not been sufficiently verified by external reviewers.

Short-term goals for research include therefore new holistic assessments and updates of existing studies in the following areas:

- Mobility and logistics (infrastructure, individual mobility and transportation of goods). Studies like Lähteenoja *et al.* [56] should be done for different countries and for Europe as a whole;
- Construction and housing including infrastructure as well as individual preferences and habits [36];
- Mobility and communication (e.g., focusing products for information and communication technology (ICT) and physical mobility to explore low resource shifts between both);
- Energy production (further update) and electrical grids (macro and micro models);
- Nutritional turn via lifestyle changes supported by common defined strategies developed by public and private catering establishments, producers, retailer, politicians and households.

Central topics for developing methods and methodologies are:

- Extended resource efficiency analysis to screen processes, products, sectors, activities and lifestyles of high relevance and dematerialisation potential;
- R&D on sociotechnical innovation fostering behaviour change towards low resource production and consumption patterns—transformation of social practices [36,161,163];
- Sustainable service design and new business models;
- Integration of other sustainability and resource management/value chain management approaches;
- Scenario development (e.g., [135]) and modeling—Integration with agent based modeling;
- Breakdown of resource targets on a per day and per year per person level for illustrating and giving input for development of products, services, infrastructures, *etc.*

The results of a MIPS analysis can deliver data for future-oriented scenarios and modeling, as well as vision development, roadmaps and foresight processes. Together with the macro application of TMC, MIPS delivers the potentials for a more system-oriented resource management. However, integrated and future oriented applications and approaches remain to be developed and proofed.

Author Contributions

The authors have contributed to the paper in several ways. Liedtke, Lettenmeier and Rohn especially have contributed in (further) developing the MIPS approach in collaboration with Friedrich Schmidt-Bleek. All authors have conducted MIPS studies and contributed to the paper through their expert knowledge in data gathering, calculating, and interpreting MIPS results. Liedtke developed the concept and structure of the paper and did extensive work in internal reviews of paper drafts. Bienge coordinated the writing and review process and contributed especially in mainly writing the chapters Introduction together with Greiff and MIPS Concept and Methodology as well as adapting and editing the Figures. The chapter MIPS application Fields at Micro and Meso Level has mainly been written by

Wiesen and Teubler whereas Bienge developed Tables 2 and 5 in close collaboration with Liedtke. The chapter Discussion and Conclusion has been collaborative work led by Liedtke.

Conflicts of Interest

The authors declare no conflict of interest.

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