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The effect of the economic cycles on material requirements: Analysing the dematerialization in developed countries

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ABSTRACT

The evolution of resource requirements in developed countries after the 2008 crisis seemed to indicate that there is a process of dematerialization. This paper analyses dematerialization in a group of developed countries and the effects of the economic cycle on resource use. The aim is to determine whether dematerialization can be linked to the effects of the economic crisis or, on the contrary, is independent of the economic context. To do this, a descriptive part is proposed in which the existence of dematerialization over the last 50 years is analysed. Subsequently, a model is estimated in which the effect of recessionary, low-growth and normal growth periods on the consumption of material resources is contrasted. The raw material input is used as an indicator of the use of material resources, which makes it possible to link each country to all the resources it requires for the normal functioning of its economy, regardless of where they are consumed. Among the main results, it can be noted that reductions in resource consumption occur in periods of recession and low growth, while for growth above 2% there is no dematerialization.

1. Introduction

There is currently an ongoing debate on dematerialization, understood as the reduction of the amount of resources required by an economy while maintaining economic growth. Thus, for some research trends, the most developed countries tend to modify their economic structure towards less materially intensive activities, which would enable them to achieve dematerialization and decarbonization (Ayres and van den Bergh, 2005; Grossman and Krueger, 1995; Shafik and Bandyopadhyay, 1992; Steinberger et al., 2013; Wiedmann et al., 2015). Although this issue has been widely studied, there is no clear consensus on the direction of the relationship between the two variables, and there is a wide divergence in the results obtained in different studies (Allard et al., 2018; Ansari et al., 2020; Schandl et al., 2016b; Steinberger et al., 2010, 2013; Wiedmann et al., 2015).

An important factor in the analysis of dematerialization is the calculation of each country's material use. For a long time, studies based on a territorial approach have predominated, which accounts in trade flows simply for the final goods traded. However, the globalization of the economy has made it necessary to rethink the suitability of this procedure, considering that richer countries tend to specialize in less materially intensive activities and vice versa (Carpintero et al., 1999; Duro and Teixidó-Figueras, 2013; Fernández-Herrero and Duro, 2019). When methods that count as part of each country's material requirements all the resources used in the production of the goods that are consumed in its economy (even if they are produced elsewhere in the world) are applied, dematerialization is a much less frequent phenomenon (Kemp-Benedict, 2018; Schandl et al., 2018; Wiedmann et al., 2015).

The study of the context in which the reduction in resource use occurs is also of great importance. Gross Domestic Product (GDP) is a much debated indicator because of its ability to approximate the level of development of a country (Fitoussi et al., 2011; Giannetti et al., 2015; Kubiszewski et al., 2013). However, the fact that material use is reduced in a context of recession or low growth may raise doubts about a process of dematerialization actually occurring. If normal economic growth is not compatible with the reduction of material requirements, it would be difficult to sustain the dematerialization theory and would need a rethinking of growth-centred economics.

Although the reduction of resource use is essential, the economic context in which it is achieved is very relevant. If it is accepted that economic growth is associated with greater welfare, dematerialization

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conditioned to very low levels of growth could negatively affect the living standards of the population. Although there is a great deal of research focused on dematerialization, the conditions under which it occurs are not often analysed. For example, the effects of the 2008 crisis were not restricted to the monetary sphere, but also affected final resource consumption, marking a turning point in many developed countries. Since then, several research studies have appeared that attempt to determine the extent to which dematerialization processes respond to structural change or to the effects of economic crises (Schaffartzik and Duro, 2022; Shao et al., 2017).

The main objective of this article is to investigate the influence of the economic cycle on dematerialization. Specifically, it analyses the relationship between the level of economic growth or degrowth and the use of material resources. In this way, it is possible to identify under which economic conditions the material requirements are more likely to be reduced. This makes it possible to test the dematerialization hypothesis that, in developed countries, economic growth favors the reduction of resource use. To this end, a two-phase analysis is proposed: in the first phase, the evolution of resource use, GDP, and dematerialization between 1970 and 2018 is analysed; in the second phase, a model is proposed, including other variables of interest, which will make it possible to quantify the relationship between resource use and periods of recession, low economic growth and normal growth. In this way, it is intended to determine the effect of the economic cycle on material requirements. In addition, other issues of interest related to the dematerialization theory are studied, such as the effect of the growth of the service sector on material use.

The analysis is focused on a set of 23 countries[1] with a high level of development, selected based on their Human Development Index in 2022 and considering the restrictions imposed by data availability. The period analysed has been determined based on data availability, covering 1970 to 2018.

The main contribution of this research lies in the use of a consumption perspective in the determination of material use. Studies with a similar approach, such as Shao et al. (2017) and Kassouri et al. (2021), employ domestic material consumption, so that the results do not show the effects of international trade and productive relocations. At the same time, these studies do not focus on a set of developed countries, so they do not allow us to accurately test the dematerialization hypothesis in developed countries. In addition, this research focuses on materials linked to economic activity (Raw Material Input), instead of materials related to the final demand of each country (Raw Material Consumption or Material Footprint). This makes it possible to analyse dematerialization by considering all the materials mobilized by a country's economic activity, regardless of what its inhabitants consume. Thus, a more accurate approximation of the relationship between economy and material use is achieved.

The article is structured as follows: section 1 presents a general introduction to the problem under study, followed by a description of the methodology, the data used, and the analysis model proposed in section 2. The results of the analysis are then presented, both from the descriptive perspective of dematerialization and the estimation model. Section 4 includes the discussion of the results in relation to the literature review considered in this research.

2. Methodology, literature review and data

2.1. Material resource requirements

The quantification of the material requirements of the countries is carried out through Material Flow Accounting (MFA). This methodology determines the physical flows that occur between society and nature, valuing the physical requirements of a territory (Fischer-Kowalski et al., 2011; Matthews et al., 2000).

To measure the resources consumed by an economy, the starting point is domestic extraction, which comprises all those material resources extracted from nature that become part of the economic process (Schandl et al., 2016a). This implies that materials that are extracted but are not monetarily valued are not accounted for. From domestic extraction, physical exports are deducted, and imports are added to obtain material consumption. Usually, trade flows represent the weight of the materials contained in the goods exchanged. In this way, an indicator of material consumption known as domestic material consumption (DMC) is obtained, which indicates the consumption of materials produced within the territory under analysis (Eurostat., 2018; Schandl et al., 2016a).

This way of measuring material consumption can be somewhat limited in an economic context where international trade is of great importance. For this reason, analysing through a consumption perspective is more appropriate, whereby trade flows account not only for the materials contained in the traded goods, but also for the materials used in their production (Eurostat., 2018; Schandl et al., 2016a). The indicator obtained is known as Raw Material Consumption (RMC) or Material Footprint and provides a measure of the amount of resources mobilized by the final consumption of a country, regardless of the fact that not all of them are actually consumed in this country (Eurostat., 2018,; Schandl et al., 2016a).

However, when it comes to investigating the resources required for economic activity, Raw Material Input (RMI), the sum of DE and material imports (in raw materials equivalents) is a more appropriate measure. While the Material Footprint provides a measure of the resources linked to final demand or the size of a territory's metabolism, the RMI represents the material scale of a country's economy (Eurostat., 2018). It is therefore more suitable for analysing the evolution of the economy's material requirements and the effect of the economic cycles.

The data is obtained from the Global Material Flows Database of the United Nations Environment Programme (UNEP, 2022). In addition to the total RMI, we will use the RMI divided into four major categories defined according to those described in the Global Material Flows Database (UNEP, 2022), which are the following:

- Biomass: comprises all biotic resources from the earth's crust, including crops, livestock, or forested areas, among others. They constitute a basic material category for people, as they include food.
- Fossil fuels: refers to fossil energy sources and their derivatives, mainly oil, gas, and coal. These materials are the basis of the energy system of most of today's societies.
- Metal Ores: refers to the group of minerals that are good conductors of electricity, are malleable and have a brightness of their own, such as gold, iron, copper, or mercury. These materials have many applications in industrial societies.
- Non-metallic minerals: correspond to the group of minerals that lack their own luster and are not good conductors of electricity, among which are granite, gravel, or sand. These materials are widely used in construction.

2.2. Decoupling and dematerialization

The situation in which there is simultaneous GDP growth and a decrease in resource use is known as dematerialization. The study of dematerialization allows us to conclude what effect economic growth has on the use of material resources.

There are multiple techniques that allow us to analyse the relationship between GDP and material requirements. In this research, we have chosen the Tapio Decoupling Index (TDI), an indicator that shows the elasticity of material use with respect to GDP (Tapio, 2005). One of the

[1] Australia, Austria, Canada, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Japan, Netherlands, New Zealand, Norway, Portugal, Korea, Singapore, Spain, Sweeden, Switzerland, United Kingdom (UK) and United States of America (USA).

main advantages of this indicator is the simplicity of its interpretation, as well as its ability to indicate whether there is decoupling, dematerialization or rematerialization. The calculation of this indicator can be expressed as follows:

$$TDI = \frac{\%\Delta\ MR}{\%\Delta\ GDP} = \frac{(MRt - MRt_0)}{MRt_0} \Big/ \frac{(GDPt - GDPt_0)}{GDPt_0}$$

Therefore, the TDI simply shows the relationship between the variation in material use and the variation in GDP between two selected periods. Thanks to the simplicity of its calculation and interpretation, it is a widely used indicator in different research projects (Papież et al., 2021; Song et al., 2020; Wang et al., 2019; Zhuang et al., 2022) and institutional reports (UNEP, 2011).

Although the interpretation of the TDI is simple, there is a large framework for interpreting the results (Dong et al., 2021; Song et al., 2020; Tapio, 2005; Yu et al., 2017). Table 1 shows a framework for the interpretation of the TDI adapted to the needs of this research:

In the usual classification of TDI results, reference is often made to decoupling. Decoupling implies a separation between the evolution of GDP and that of material use that can occur in different ways. When it occurs because material requirements grow to a lesser extent, the decoupling is weak, since it implies lower consumption per unit of GDP, but growing consumption. In the case where the decoupling occurs because of a decrease in resource use while maintaining GDP growth, it is considered strong decoupling. It is the latter case that can be identified with dematerialization, as it is the only situation in which resource use is effectively reduced without negatively affecting GDP.

2.3. Model and data

To achieve the objectives defined in this research, the following model is proposed, which relates the material requirements to a series of variables:

$$RMI = a(R) + b(LG) + c(NG) + d\left(GDP_{pc}\right) + e(\%UP) + f(\%CVA) + g(\%SVA) + h$$

The model is proposed with the RMI as the dependent variable, with the aim of finding the determinants of the evolution of resource use. Logarithmic scale is used in the RMI and GDP, to facilitate the interpretation of the results. A panel data set is available and is estimated using the most appropriate method according to the results of the tests presented in the results.

To determine the effect of the economic cycle on the evolution of resource requirements, three dummy variables have been defined to identify those periods in which there is recession (R), low growth (LG) or normal growth (NG). These variables take values 0 or 1 depending on whether or not each of these situations occurs. In this way, it is possible to determine whether or not dematerialization occurs in each of the situations. For this purpose, data on the year-on-year GDP growth rate are used. The variable R takes a value of 1 in recessionary periods, i.e. when growth is negative. LG takes a value of 1 in periods when growth is between 0% and 2%. Finally, the variable NG takes a value of 1 when growth is above 2%, which can be considered normal growth. Although it is common to consider 3% as a normal growth rate, it is expected that in the coming decades the average growth rate in developed countries will not exceed 2% (Alfredsson and Malmaeus, 2017; Malmaeus and Alfredsson, 2017).

To improve the model results and check their consistency, several additional variables have been included. The first of these is GDP in constant 2015 dollars. GDP is the quintessential measure of the size of an economy, so its inclusion in the model makes it possible to determine how economic growth affects material requirements.

%UP indicates the percentage of the population residing in urban areas. A high proportion of urban population is a characteristic of countries living in an industrial metabolic regime, characterized by a level of utilization and dependence on material resources far in excess of human needs (Fischer-Kowalski and Schaffartzik, 2015; Shao et al., 2017). In the same way, the process of urbanization of the population implies a large consumption of material resources for buildings and infrastructures (Schiller and Roscher, 2023). Therefore, it is to be expected that the results indicate a positive relationship between this variable and the RMI per capita.

%CVA indicates the percentage of value added coming from the construction sector. Its inclusion is considered of interest because of the close relationship of this sector with the increase in urban population and because of the links of the 2008 crises with the construction sector. Moreover, although in the most developed countries the construction sector is not usually of great importance in monetary terms, it represents up to 60% of the RMI in some countries. Thus, the evolution of this variable can be considered as a control variable in the model.

%SVA indicates the percentage of a country's value added that comes from the service sector. The size of the service sector is related to a country's level of development, so that the most developed economies tend to have a service sector weight of around 70% or even more. This sector is usually considered to have a lower material intensity than the other economic sectors (Heiskanen and Jalas, 2000), and therefore its effect on the RMI is expected to be negative.

Data for *GDP*, *%CVA* and *%SVA* are from UNstat, *RMI* is from Global Material Flows Database and %UP from the World Bank's World Development Indicators database. The period analysed spans from 1970 to 2018, adjusting for data availability for *RMI*. A summary of the data used for the estimation of the model and the sources from which they were obtained is shown in Table 2.

Table 1
Framework to the interpretation of the Tapio Decoupling Index,

Category	Subcategory	GDP	MC	TDI
Decoupling	Strong Decoupling or dematerialization (SD)	>0	<0	≤0
	Weak Decoupling (WD)	>0	>0	0 < TDI < 1
	Negative Decoupling (ND)	<0	>0	≤0
Coupling	Recessive coupling (RC)	<0	<0	≥ 1
	Expansive coupling or rematerialization (EC)	>0	>0	≥ 1

Source: own elaboration adapted from Tapio (2005).

2.4. Research limitations and possible ampliations

One of the main limitations of this work comes from the limited availability of data. The Global Material Flows Database only contains RMI data between 1970 and 2019. However, the latter period is an estimate and is not suitable for inclusion in a model, so it has been excluded from the analysis. Another limitation arises from the level of disaggregation of the RMI, as only 4 major categories are available. A greater disaggregation would allow for a more detailed analysis of the evolution of the different sectors.

The TDI is a useful indicator for interpreting evolution over short periods of time, but due to the way it is calculated, it loses explanatory

Table 2
Summary of variables used in the model.

	1970	2007	2018	Source
GDP_{pc} ($)	Mean: 18.879,55	Mean: 43.839,63	Mean: 47.637,81	UNStat
	Min.: 1.977,07	Min.:19.942,78	Min.: 18.626,78	
	Max.: 54.093,62	Max.: 81.804,85	Max.: 88.063,19	
RMI_{pc} (tons)	Mean: 28,85	Mean: 46,50	Mean: 41,60	Global Material Flows Database, UNEP
	Min.: 7,80	Min.: 23,06	Min.: 16,58	
	Max.: 69,11	Max.: 92,90	Max.: 113,97	
Urban Population %	Mean: 69,89%	Mean: 79,07%	Mean: 81,26%	World Development Indicators, World Bank
	Min.: 40,70%	Min.:58,75%	Min.: 58,30%	
	Max.: 100%	Max.: 100%	Max.: 100%	
Construction %	Mean: 8,04%	Mean: 6,45%	Mean: 5,54%	UNStat
	Min.: 4,39%	Min.: 3,15%	Min.: 1,56%	
	Max.: 15,47%	Max.: 11,67%	Max.: 7,91%	
Services %	Mean: 55,51%	Mean: 69,97%	Mean: 72,44%	UNStat
	Min.: 43,47%	Min.: 56,71%	Min.: 59,86%	
	Max.: 68,79%	Max.: 77,50%	Max.: 80,25%	

Source: own elaboration based on data from Global Material Flows Database, UNstat and World Bank.

capacity in the long term. This is because the farther apart the initial and final periods are, the more intermediate variations are omitted in the calculation.

On the other hand, several developed countries have been selected in the analysis according to the Human Development Index criterion in 2022. These countries do not maintain the same level of development throughout the entire time sample, so that the selection could vary if it were based on the HDI of another year. In addition, there is significant heterogeneity among the countries analysed. Although this has positive aspects, because it allows to include in the analysis different scenarios and trajectories, it also worsens the quality of the estimates. The results of the model are not fully generalizable, although they provide useful and relevant information.

The main extension of this work could be done by making more recent data available, which would allow the effects of the Covid-19 pandemic or the effects of the Ukrainian war to be included in the analysis. These distortions may provide new relevant information to determine the degree of coupling between resource use and economic growth.

3. Results

3.1. Descriptive section

This section provides a first descriptive approach to the analysis of dematerialization and different statistics of interest. A preliminary issue that is interesting to analyse is the difference between the material resources consumed by the final demand of each country (material footprint or raw material consumption) and the resources mobilized by economic activity (RMI). Fig. 1 shows both variables in tons per capita for each country.

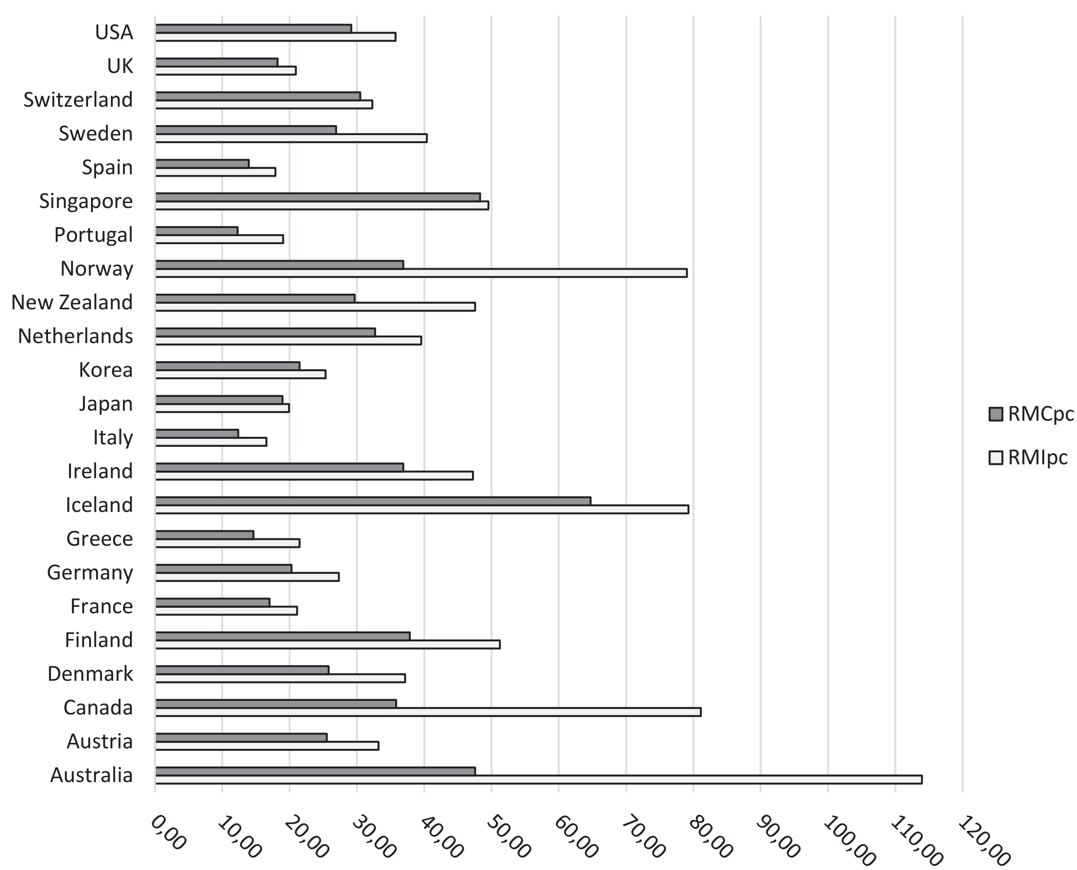

Fig. 1. RMC and RMI per capita, year 2018.
(Source: own elaboration based on data from Global Material Flows Database.)

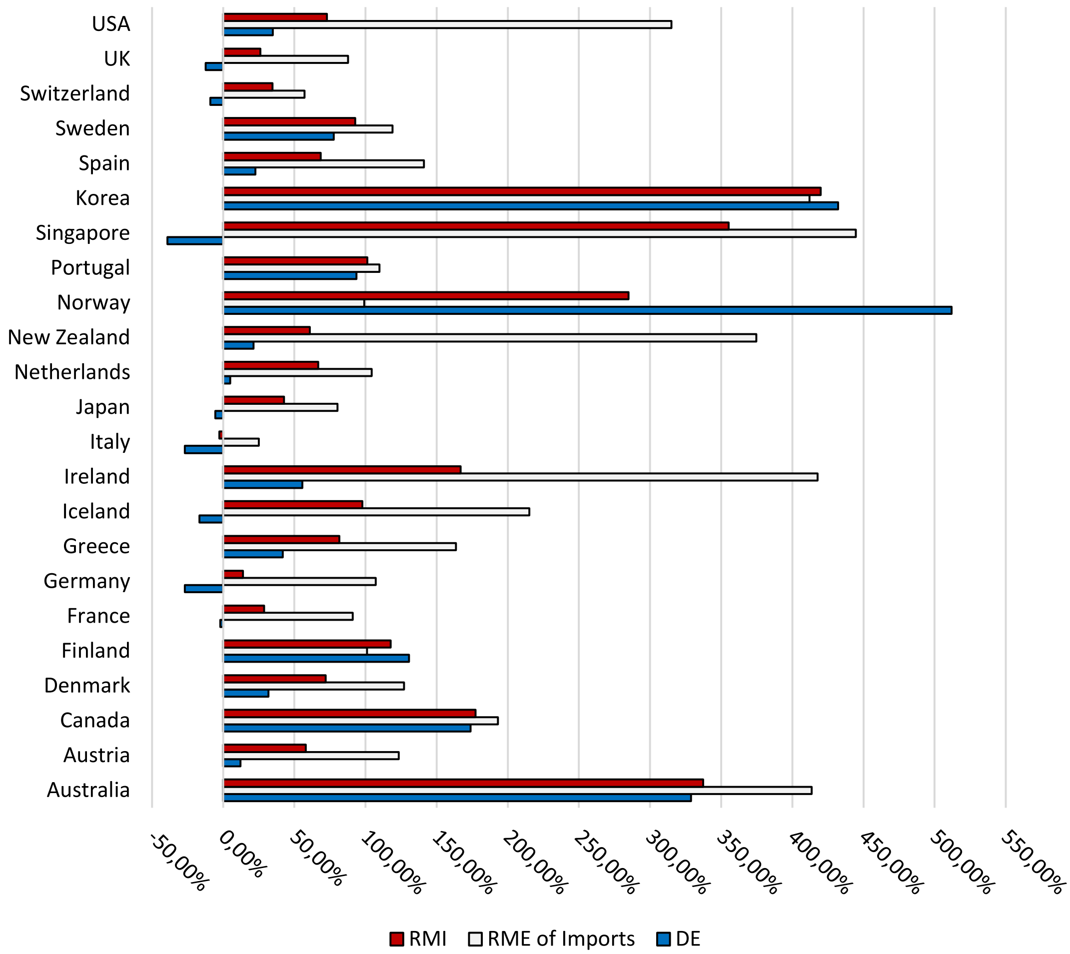

Fig. 2. Variation between 1970 and 2018 in DE, RME of imports and RMI (%). (Source: own elaboration based on data from Global Material Flows Database.*)*

Although the RMI will always be greater than the RMC, the greater the difference between the two, the greater the gap between the material resources required by final demand and those mobilized by economic activity. The difference is considerably greater in countries with a large endowment of certain material resources, such as Australia, Canada, and Norway. In this context, it is interesting to detail the evolution of the RMI and its components. Fig. 2 depicts the evolution of DE, RMI and RME of imports between 1970 and 2018.

RMI increases in all cases, except for Italy. Thus, practically all the economies analysed have increased their material scale between 1970 and 2018, which is an indication contrary to an eventual dematerialization. The widespread increase in material requirements occurs either through increased domestic extraction or by importing materials from the rest of the world (or a combination of both). DE is the only variable for which reductions are observed, mainly localized in countries with limited material endowments or that have tended to deindustrialize.

In the field of dematerialization, Fig. 3 shows the TDI for all the countries included in the analysis. The TDI has been calculated for three different periods: the total years analysed (1970–2018), the years before the 2008 crisis (1970–2007) and the years after (2007–2018).

All countries are at relative decoupling or rematerialization values in the 1970–2007 and the 1970–2018 periods, while only Italy reach dematerialization in the 1970–2018. In contrast, a vast majority of countries reach dematerialization in the period 2007–2018, coinciding with the economic crisis and its effects in later years. This is a clear symptom that it is from 2007 onwards that a reduction in the economy's material requirements is most likely to be found.

Table 3 shows the proportion of periods with recession, low growth and normal growth in the different time intervals considered. It is noteworthy that between 1970 and 2007 > 70% of the periods show GDP growth above 2%. On the other hand, between 2008 and 2018, the percentage drops to almost half, while the number of periods in recession doubles and the number of periods with low growth increases considerably.

3.2. Model results

For the estimation of the proposed model, a panel data sample has been estimated by ordinary least squares, considering the results of the applied tests. The results of the tests applied for the selection and validation of the models are shown in Annexes 1 and 2. In no case are there problems of multicollinearity or non-normality in the distribution of the residuals. Both RMI per capita and GDP per capita have been converted to a logarithmic scale to improve the results and facilitate their interpretation.

Table 4 shows the estimation results of the proposed model for the entire RMI. In all cases, we find a positive effect of GDP, the proportion of urban population and the percentage of the construction sector on gross value added. Likewise, the share of the services sector on gross value added has a negative effect on the RMI, so these variables show the expected result.

The effect of GDP is as expected, considering that there is a significant coupling between GDP and RMI throughout most of the years analysed. The scarcity of periods in which dematerialization is achieved was anticipated, which confirms this result: the growth of GDP increases material resources requirements.

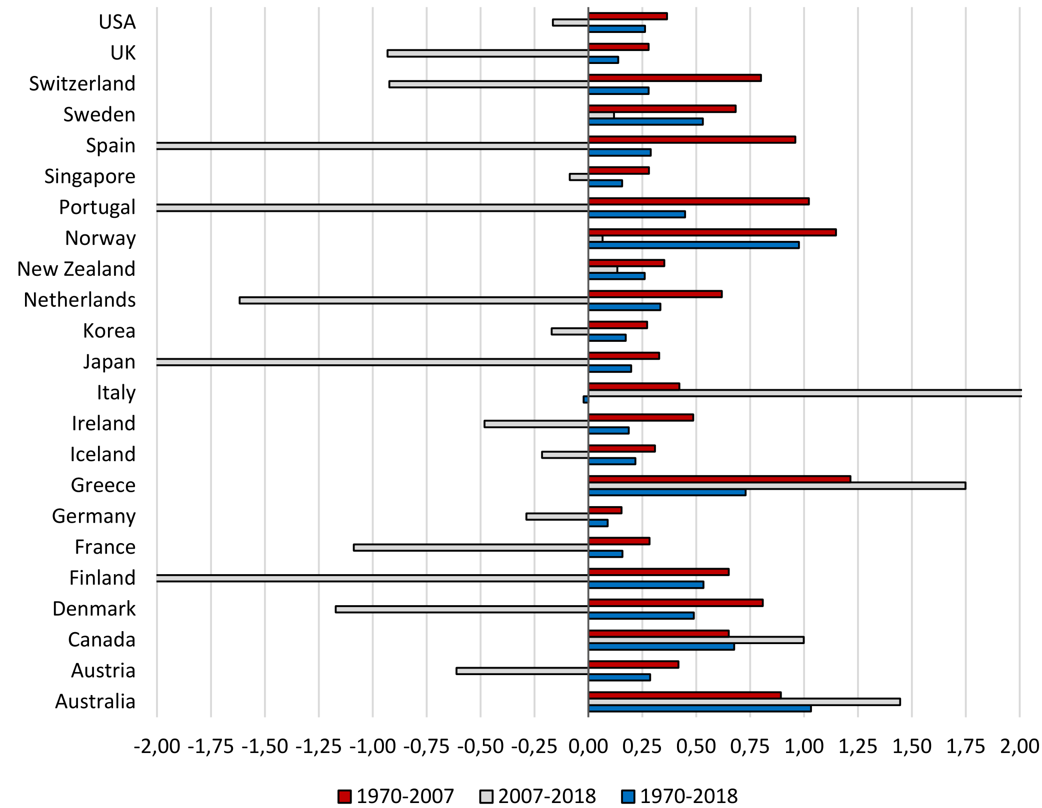

Fig. 3. TDI by country in different selected periods.
(Source: own elaboration based on data from Global Material Flows Database.)

Table 3
Ratio of periods in recession, low growth, and normal growth.

	1970–2018	1970–2007	2008–2018
Recession	132/1104 (11,96%)	81/851 (9,52%)	51/253 (20,16%)
Low growth	261/1104 (23,64%)	166/851 (19,50%)	94/253 (37,15%)
Normal growth	711/1104 (64,40%)	604/851 (70,98%)	108/253 (42,69%)

Source: own elaboration based on data from UNstat.

Table 4
Model results for the RMI.

Variable	Recession	Low growth	Normal growth
Recession	−0,025 (0,034)		
Low growth		−0,120 (0,026)***	
Normal growth			0,107 (0,023)***
GDP	0,874 (0,008)***	0,875 (0,008)***	0,874 (0,008)***
Urban Population %	0,393 (0,079)***	0,374 (0,078)***	0,367 (0,078)***
Construction %	0,170 (0,042)**	0,158 (0,042)***	0,158 (0,042)***
Services %	−0,862 (0,125)***	−0,813 (0,124)***	−0,791 (0,124)***
R^2	0,925	0,926	0,926

Source: prepared with data from Global Material Flows Database, UNstat and World Bank. Standard error is shown in parentheses.

On the other hand, the estimation indicates that recessionary periods have no significant effect on RMI. Periods of low growth do have a negative and significant effect on the RMI, while periods of normal or higher growth have a positive and significant effect. Therefore, the possibilities of dematerialization are concentrated in periods of moderate economic growth (below 2%). On the other hand, normal growth is related to an increase in physical requirements. This result is consistent

Table 5
Model results for biomass.

Variable	Recession	Low growth	Normal growth
Recession	−0,054 (0,045)		
Low growth		−0,150 (0,035)***	
Normal growth			0,145 (0,031)***
GDP	0,773 (0,011)***	0,775 (0,011)***	0,773 (0,011)***
Urban Population %	0,959 (0,105)***	0,937 (0,104)***	0,926 (0,104)***
Construction %	0,238 (0,056)***	0,224 (0,056)***	0,223 (0,056)***
Services %	−0,902 (0,166)***	−0,847 (0,165)***	−0,811 (0,165)***
R^2	0,844	0,846	0,847

Source: prepared with data from Global Material Flows Database, UNstat and World Bank. Standard error is shown in parentheses.

Table 6
Model results for fossil fuels.

Variable	Recession	Low growth	Normal growth
Recession	−0,045 (0,078)		
Low growth		−0,224 (0,060)***	
Normal growth			0,196 (0,053)***
GDP	0,889 (0,019)***	0,891 (0,019)***	0,889 (0,019)***
Urban Population %	1361 (0,181)***	1326 (0,180)***	1314 (0,180)***
Construction %	−0,223 (0,096)**	−0,245 (0,096)**	−0,244 (0,096)**
Services %	−0,991 (0,286)***	−0,899 (0,284)***	−0,860 (0,286)***
R^2	0,721	0,725	0,725

Source: prepared with data from Global Material Flows Database, UNstat and World Bank. Standard error is shown in parentheses.

Table 7
Model results for non-metallic minerals.

Variable	Recession	Low growth	Normal growth
Recession	−0,005 (0,019)		
Low growth		0,007 (0,015)	
Normal growth			−0,003 (0,013)
GDP	0,015 (0,005)***	0,015 (0,005)***	0,015 (0,05)***
Urban Population %	−0,095 (0,050)**	−0,093 (0,044)**	−0,094 (0,044)**
Construction %	0,179 (0,023)***	0,180 (0,023)***	0,179 (0,023)***
Services %	0,066 (0,069)	0,061 (0,069)	0,062 (0,069)
R^2	0,060	0,060	0,060

Source: prepared with data from Global Material Flows Database, UNstat and World Bank. Standard error is shown in parentheses.

Table 8
Model results for metal ores.

Variable	Recession	Low growth	Normal growth
Recession	−0,037 (0,078)		
Low growth		−0,216 (0,059)***	
Normal growth			0,189 (0,053)***
GDP	0,889 (0,018)***	0,891 (0,018)***	0,889 (0,018)***
Urban Population %	2070 (0,178)***	2036 (0,177)***	2025 (0,177)***
Construction %	0,088 (0,095)	0,067 (0,095)	0,067 (0,095)
Services %	−1428 (0,078)***	−1338 (0,281)	−1299 (0,282)***
R^2	0,718	0,722	0,721

Source: prepared with data from Global Material Flows Database, UNstat and World Bank. Standard error is shown in parentheses.

with the positive effect of GDP on RMI.

Table 5, Table 6, Table 7, and Table 8 show the model estimation results for biomass, fossil fuels, non-metallic minerals, and metallic minerals respectively. The model estimation with biomass as the dependent variable provide results in the same sense as for the RMI case, but with different effect sizes. The effect of GDP is lower, while that of urban population, construction and the service sector is higher. The effects of the different types of business cycle are also consistent with those of the full RMI.

With respect to the model estimated for fossil fuels, does not present greater differences. The most noticeable change is the negative effect of the construction. Also, there is an increase in the effect of the urban population, which can be attributed to a greater intensity in the use of fossil fuels in large agglomerations and in more developed areas. The effect of periods of low growth is greater, but so is the effect of periods of growth above 2%.

Non-metallic minerals result in a very poor fitting model. The GDP effect remains positive, although its size is greatly reduced. The urban population starts to have a positive effect. Given that the development of urban agglomerations requires a high quantity of these materials, it is expected that the most urbanized countries will tend to consume smaller quantities of these. Another variation comes from the change in the direction of the construction effect, which is totally coherent given the connection between this economic sector and this material category. Finally, the effect of the economic cycle is not significant on non-metallic minerals.

Regarding the model estimated for metals, the effect of the different degrees of growth is recovered for the case of low and normal growth, in the same sense as the RMI. The GDP intensity is also similar and increases the effect of both the urban population and services. On the other hand, construction does not show a positive effect on this material category.

4. Discussion

4.1. Dematerialization and economic cycle

Between 1970 and 2018, dematerialization is far from being a widespread event in the countries analysed. Most of the periods in which the TDI is negative are concentrated in the years following the 2008 crisis, implying that there may be a connection between the change in the economic cycle and the reduction in resource use. Through the TDI, most of the countries analysed show no dematerialization between 1970 and 2007, while since 2007 the reverse is true. This implies that dematerialization, if it exists, occurs mainly after the 2008 crisis, in line with the hypotheses put forward in this research.

The results of the model proposed for the RMI indicate that there is no definite effect of recessionary periods on material requirements, but they decrease when GDP growth is below 2%. When growth levels are higher than 2%, the RMI increases, results that coincide with other studies with a similar approach, but based on material consumption (Kassouri et al., 2021; Shao et al., 2017). Therefore, dematerialization would only be achieved when economic growth is low (below 2%). It is worth noting that there are almost twice as many periods of low growth as recession, and it is not common to have several consecutive recession periods, but they are usually followed by several years of low growth. Therefore, it is expected that a crisis will have effects on the RMI in the years following the fall in GDP, which usually correspond to low growth. It should also be considered that GDP oscillations are faster because it is a monetary magnitude that does not have a completely physical basis.

This relationship is reproduced in the same way in all material categories, except for non-metallic minerals, for which no growth classification is significant. Non-metallic minerals are closely linked to the construction sector, which evolves in a very heterogeneous way from country to country and shows very abrupt changes related to the 2008 crisis(Schaffartzik and Duro, 2022; Shao et al., 2017). Another relevant factor is that the sectors intensive in these materials, mainly construction, do not usually represent a fundamental part of the economic structure. This manifests in a much more moderate effect on GDP. Therefore, it is reasonable that there is a greater dissociation between the evolution of the economy and the use of these materials. The rest of the categories have a much closer link with economic evolution, since they include basic goods related to food, energy and industrial production (Krausmann et al., 2017). The strongest effects appear in the fossil fuels, which are the most influenced by the economic cycle. Fossil fuels can be considered a critical material category, since they have a very large impact in the form of emissions and are likely to present shortage problems in the medium term if the rate of consumption is maintained (Capellán-Pérez et al., 2015). At the same time, they are a fundamental element for the functioning of the economy.

Regarding the evolution of resource use in periods of normal growth or high growth, it is clear that growth rates that are considered favourable for the economy are not favourable in ecological terms. Furthermore, the effect of GDP on RMI is positive and significant in all categories, which implies that there is relative decoupling. While this implies an improvement in terms of material intensity, it also implies an increase in resource requirements as GDP increases. In view of the results obtained for the dichotomous variables, the positive relationship appears to be reinforced the higher the GDP. This leads to the need to rethink new economic models that are not based on continuous growth.

Based on the results, it is possible that the increase in resource requirements will slow down or even decrease due to a slower pace of economic growth. The concentration of dematerialization periods in the years after 2008 is more favourable to this hypothesis than to that of a possible lasting structural change. Considering the limitations of GDP to represent the living conditions of the population, the underlying cause could be found in a stagnation of the improvement of living standards in developed countries. In this context, dematerialization should become a way to maintain the quality of life with less resource use.

4.2. Control variables

The percentage of urban population is associated with a higher use of resources of all material categories, except in the non-metallic minerals. This result is consistent with the fact that in a more urban territory there is less need to use these materials, since buildings and infrastructure have already been developed to a greater extent. This result does not coincide with other studies related to emissions with a territorial approach (Hong et al., 2022; Ribeiro et al., 2019), that indicate that urban agglomerations have advantages in terms of lower use of individual transportation or energy savings derived from housing blocks. Despite of whether the material requirements of an urban area are larger or smaller, the results show that the larger the urban area, the larger the material scale of the economy.

Regarding the weight of services on value added, it can be observed a generalized negative effect. Only in the case of non-metallic minerals is there a non-significant relationship, maybe because to its high dependence on different devices and infrastructures that use these materials (Carpintero, 2003; Carpintero and Nieto, 2021). These results are consistent with the literature and research indicating that the development of this sector promotes a reduction in material intensity (Heiskanen and Jalas, 2000).

About the weight of construction on gross value added, the result is as expected. Considering that non-metallic minerals are closely related to this sector and, at the same time, represent between up to a 60% of the total RMI, it is expected that the evolution of this sector will have an important and direct effect on the use of resources. Fossil fuels are the only category where construction has a negative effect. This can be attributed to the fact that construction is a less energy-intensive sector than most industrial sectors. Thus, as a country's industry develops and gains weight, the use of fossil fuels may increase while the use of non-metallic minerals decreases, due to a drop in construction activities resulting from a more mature infrastructure.

5. Conclusions and policy implications

This research has studied the influence of the economic context on the evolution of material requirements, and on dematerialization in the period 1970–2018, through Tapio's decoupling index and a model estimation. The data used have been obtained through the MFA, using consumption approach and de RMI indicator, which allows to estimate de material dimension of the economy. The results obtained, both from the descriptive perspective and from the applied model, allow us to highlight the following conclusions:

- In the set of countries analysed, the periods in which dematerialization is achieved are mainly concentrated in the years after 2007. Therefore, after the 2008 crisis, it is much more likely that a country's resource use will be reduced, and dematerialization will be achieved.
- Recessionary periods are relevant for the material use evolution. to a decrease in resource use. This may be linked to the fact that recessionary periods are relatively rare, and their effects would extend to later periods.
- Periods of economic growth of <2% are associated with reduced material requirements, and that these are the only periods in which dematerialization is achieved. This effect occurs in all material categories, except non-metallic minerals.
- For GDP growth above 2%, there is no evidence of dematerialization. Above this level, GDP and RMI maintain a positive relationship, so a normal growth leads to an increase in the material requirements. Dematerialization is only likely to occur under low-growth rates.
- The growth of the service sector favors dematerialization, but the urban population is linked to a higher material requirement.

On the other hand, the results of this research have policy implications of great relevance for the design of efficient economic and environmental policies. Based on these results, the following recommendations are considered appropriate:

- Rethink the economy based on unlimited economic growth, in view of the relationship between economic growth and resource requirements. In this regard, it is particularly important to design an ecological transition that breaks with material dependence.
- Define new indicators, beyond GDP, that make it possible to establish objectives based on improving or maintaining quality of life while preserving available resources and the environment. Could be considered multifactor indicators, capable of capturing economic performance, material and energy intensity, and living conditions.
- Explore options related to steady state and economic degrowth, especially considering that there is a significant mismatch between the materials mobilized by economic activity and those required by the metabolism of each country.

CRediT authorship contribution statement

Pablo Alonso-Fernández: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rosa María Regueiro-Ferreira:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Annex 1. Contrast for the selection of the estimation method and normality of the residuals

	Panel (Breusch-Pagan)	Normality (Chi-Square)
RMI	p-value >0,05	*p*-value >0,05
B	p-value >0,05	p-value >0,05
FF	p-value >0,05	p-value >0,05
NMM	p-value >0,05	p-value >0,05
MO	p-value >0,05	p-value >0,05

Annex 2. Variance inflation factors (VIF) for the different variable combinations

	GDP	%UP	%Con	%Ss	Dummy
Recession	1,352	1,284	1,383	1,866	1,008
Low growth	1,350	1,287	1,385	1,878	1,031
Normal growth	1,350	1,291	1,386	1,896	1,043

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