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How to spend 750 billion euro? Applying sacrifice theory to determine Covid-19 compensations in the EU

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Abstract

In this note we consider an economic union consisting of sovereign national states. An asymmetric shock hits the union and as a result it decides to set up a fund in order to compensate the countries in the union. We show how sacrifice theory can be used to determine the compensation payments for the countries in a way such that the relative damages after compensation are equal across countries. Finally, we apply our results to determine the Covid-19 compensation payments in the EU

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1 Introduction

According to the EU Commission, the 'Next Generation EU' program is intended to help Member States to address the challenges caused by the Covid-19 pandemic. Thus, the EU Commission wants to compensate losses brought about by Covid-19 and to bring back the economies to durable growth. The fund comprises 750 billion euro and is generated by issuing debt on behalf of the EU (see European Commission, 2020).

When allocating the resources across EU Member States, possible criteria could be the losses in GDP caused by Covid-19 or a combination of the losses in GDP and of the rise in unemployment, as suggested by Heinemann (2020). There, a simulation has been performed demonstrating how the funds would be allocated if those criteria were resorted to. The use of those criteria can be justified by models for fiscal insurance systems that posit that payments are guided by either fluctuations in growth or by unemployment.

In this note we follow a different approach. We resort to sacrifice theory (see e.g. Lenzi, 2008) to determine the allocation of resources from a joint fund in an economic union that has been set up in order to compensate the damages caused by an exogenous shock that hits the economies in an asymmetric manner. Often, sacrifice theories are resorted to in order to implement the ability-to-pay principle that is used as a justification for income taxation. A sacrifice is considered as a reduction of utility due to the tax that reduces disposable income of an individual. Typically, three different concepts are distinguished: the concept of the same absolute sacrifice, the concept of the same proportional or relative sacrifice and, finally, the concept of the same marginal sacrifice.

The concept of the same absolute sacrifice requires that each individual makes the same sacrifice in terms of the same reduction of its utility[1] as a result of the tax. This implies that the decline in utility relative to utility before taxation is smaller the higher the initial level of utility is, when the marginal utility declines and the reduction in utility is the same for all in the case of a constant marginal utility, giving a lump-sum tax. Generally, this is considered as unfair by most societies. Nevertheless, a justification for that principle can be seen in the argument that each individual in an economy benefits to the same degree from non-rivalrous public goods provided by the government so that it is justified to contribute in the same way to its financing. Thus, this principle is based on the approach of the 'justitia commutativa' (see Haller, 1973).

The same relative sacrifice is given when the decline in utility, due to income taxation, relative to utility before taxation is the same for all individuals. With this concept, individuals with a higher initial level of utility bear a higher reduction of their utility in absolute values. With a constant marginal utility this leads to a proportional tax rate, with a declining marginal utility this gives a proportional or progressive tax rate, depending on the functional form of the utility function. Consequently, individuals with

[1]The utility function is assumed to be identical for all individuals, rising in the income and continuously differentiable with a declining or constant marginal utility.

higher incomes and, thus, higher utility before taxation pay higher taxes compared to what they would have to pay if the concept of the same absolute sacrifice was applied. The basis for the same relative sacrifice can be seen in the idea of an 'justitia distributiva'.

The same marginal sacrifice finally implies that the incomes after taxes are identical for all taxpayers when the marginal utility declines, implying a progressive tax scheme of the highest degree, while it is indeterminate in the case of a constant marginal utility. This concept results from the maximization of the sum of individual utilities with respect to the tax of each individual, i.e. from welfare maximization, and minimizes the total tax burden. However, its relevance for real world economies is rather limited because it has severe shortcomings, such as the neglect of incentive problems and the assumption that the incomes of the individuals are given in the optimization process.

In the rest of this note we proceed as follows. In section 2, we apply the concept of the same relative sacrifice and same absolute sacrifice to determine the allocation of resources to the countries within an economic union that have been hit differently by an exogenous shock. Section 3 uses the theoretical results to compute the compensations for the EU 27 where we take preliminary estimates for the damages caused by Covid-19. Section 4, finally, summarizes our results and concludes the note.

2 Theoretical background

In the introduction we discussed the three sacrifice concepts. The subsequent subsection will discuss the two main sacrifice concepts, namely the same proportional sacrifice principle and the same absolute sacrifice principle and we will show that the first is the more plausible of the two. The concept of the same marginal sacrifice has significant shortcomings as mentioned earlier. For example, it leads to excessive progressivity with respect to marginal tax rates (see Richter, 1983), in the case of a concave utility function. In the case of a linear utility function, as in our case, the outcome is indeterminate and one would charge the countries starting with the richest, until all damages are covered so that the distribution of the GDP becomes more equal. Therefore, this concept is not plausible and will not be discussed further in this note.

We consider an economic union consisting of n sovereign states. An asymmetric shock hits the economies of the union causing damages S_i^v, $i = 1, \ldots, n$, in the countries with $S^v = \sum_{i=1}^{n} S_i^v$. The union sets up a fund with a total amount of Z that is distributed to the economies where each country receives Z_i, $i = 1, \ldots, n$, with $Z = \sum_{i=1}^{n} Z_i$. As regards the allocation of the resources from the fund we posit that the union wants to avoid any discrimination implying that each economy makes the same sacrifice after having received its compensation from the fund.

2.1 Same proportional sacrifice principle

A plausible approach to the discussion of welfare and distributive justice is the concept of the same proportional sacrifice that has gained broad acceptance. Suppose the union decides to allocate the resources from the fund in a way such that the damages after compensation payments, S_i, $i = 1, \ldots, n$, are equal according to the concept of the same relative sacrifice, i.e.

$$\frac{Y_1^v - (Y_1^v - S_1)}{Y_1^v} = \frac{Y_2^v - (Y_2^v - S_2)}{Y_2^v} = \ldots = \frac{Y_n^v - (Y_n^v - S_n)}{Y_n^v}$$

holds, with Y_i^v GDP in country i, $i = 1, \ldots, n$, before the shock. All variables are in real terms and measured in euro and we assume $Z_i < S_i^v < Y_i^v$. We would like to point out that we do not assume a concave utility function giving utility in an economy as a function of GDP with a declining marginal utility. The use of a strictly concave utility function may be justified when considering individuals, although it is often disputed even in this case, but, for entire economies it is not justified to assume a decreasing marginal utility of GDP. This holds because in each country there exist quite a many poor people who would benefit from higher incomes and even in rich countries there is a broad scope for public investment projects that would raise productivity and/or the well-being of the people.

The proposition 1 shows how the sacrifices after compensation are distributed and determines the allocation of resources when the concept of the same proportional sacrifice is applied.

Proposition 1 *Assume that the damages after compensation payments should be equal according to the concept of the same proportional sacrifice and let* $I = \{j \in |1 \leq j \leq n\}$. *Then, the damages after compensation are given by*

$$S_k = (S^v - Z)\left(\frac{Y_k^v}{\sum_{i \in I} Y_i^v}\right),\ k = 1, \ldots, n.$$

Further, compensation payments are determined as

$$Z_k = Z\left(\frac{Y_k^v}{\sum_{i \in I} Y_i^v}\right) + S_k^v\left(\frac{\sum_{i \in I \setminus \{k\}} Y_i^v}{\sum_{i \in I} Y_i^v}\right) - \left(\frac{Y_k^v}{\sum_{i \in I} Y_i^v}\right)\left(\sum_{i \in I \setminus \{k\}} S_i^v\right),\ k = 1, \ldots, n.$$

Proof: See appendix A. □

Proposition 1 shows that the damages in an economy, after compensation, relative to total damages just equal its GDP before the shock relative to total GDP, i.e. the relative damage after compensation is equal to its share of GDP in the union before the shock.

Thus, countries with a higher relative share in total GDP bear higher burdens, as was to be expected.

The compensation payment a country receives is given by the overall amount of the fund multiplied by its share in total GDP plus its damage before compensation multiplied by the sum of the GDP of all other economies relative to the total GDP of all economies minus the damage of all other countries multiplied by the relative GDP share of the country under consideration. The compensation payment a country receives is not as intuitive as the sacrifice after compensation it has to make, but, can be easily derived once its sacrifice has been determined (see the proof in the appendix A).

It can be realized that the payment depends on a component that is independent of the damages, the total amount of the fund, and on two components that depend on the shock, the country's own damage and the damages of all other countries. The payment is higher the larger is the fund and the higher the share of that country's GDP relative to the total GDP of all economies. Thus, this first term favors rich countries with a high GDP. Further, a country receives more compensation the more it was hit by the shock and the lower the damages of all other economies in the union are, ceteris paribus.

2.2 Same absolute sacrifice principle

In the case of the relative or proportional sacrifice we could look at aggregate values because the total sacrifice was considered relative to GDP implying that the ratio S_k/Y_k^v, $k = 1, \ldots, n$, equals the ratio s_k/y_k^v, with minor letters denoting per capita variables. For the same absolute sacrifice that does not hold because citizens of larger countries would have to bear smaller sacrifices per capita than inhabitants of smaller countries if the absolute sacrifice was the same for each country. Therefore, we have to consider per capita data of all real variables such that each citizen in the union is treated in the same way.

The same absolute sacrifice implies

$$y_1^v - (y_1^v - s_1) = y_2^v - (y_2^v - s_2) = \ldots = y_n^v - (y_n^v - s_n),$$

with the notation as above and minor letters denoting per capita variables. Proposition 2 shows how the damages are distributed and how the compensation payments are determined when the same absolute sacrifice is resorted to.

Proposition 2 *Assume that the damages after compensation payments should be equal according to the concept of the same absolute sacrifice. Then, the damages after compensation are given by*

$$s_k = \frac{s}{n},\ k = 1, \ldots, n.$$

Further, compensation payments are determined as

$$z_k = s_k^v - \frac{s^v}{n} + \frac{z}{n},\ k = 1, \ldots, n.$$

Proof: See appendix B. □

Proposition 2 shows that in the case of the same absolute sacrifice each person in the union has to bear the same sacrifice in absolute values. This would imply that the per capita GDP in each country is reduced by the same amount. That, however, neglects the fact that richer countries, measured by per capita GDP, can bear higher loads than poorer economies and would very likely not be accepted unanimously. As regards the compensation payments per capita, one realizes that each citizen in the union receives the same amount of the compensation payment per capita, z/n, plus the difference between its own damage before compensation minus the average damage in the union, $s_k^v - s^v/n$, per capita respectively.

3 Application to the 'Next Generation EU' program

To compute the compensations for the EU 27 countries, we recall the theoretical results from subsections 2.1 and 2.2 by applying the principle of the same proportional sacrifice and of the same absolute sacrifice respectively. Real GDP for 2019 was used as the proxy for GDP before Covid-19 [2]. Real GDP and population data were both obtained from the Eurostat website (cf. Eurostat, 2020 and 2020a). Regarding the damage caused by Covid-19, we used real GDP growth contractions for 2020 and obtained the data from the European commission spring forecast for April 2020 (see European Commission, 2020a). Figure 1 provides a pictorial view of the loss due to Covid-19 as a ratio of real GDP 2019. From figure 1 it can be seen that Greece, Spain, Italy, Croatia and France suffered higher losses compared to the other EU economies. EU economies such as Luxembourg, Austria, Malta and Poland experienced relative low losses as a percentage of GDP.

Next, we proceed to apply the principle of the same proportional sacrifice to calculate the compensations, the damages after compensation and the relative damages after compensation for each individual country. Similarly, we apply the concept of the same absolute sacrifice to calculate the compensations and the damages after compensation per capita for each individual country and proceed to demonstrate that the concept of the same proportional sacrifice is the more plausible option. As it stands now, there has not been a clear communication as to how the funds would be distributed. However, the discussions suggest that 500bn out of the total 750bn will be distributed as grants whilst the additional 250 will be disbursed in the form of loans.

Applying the concept of the same proportional sacrifice, we compute the two equations from proposition 1 considering two scenarios: firstly, we look at the scenario with the total compensation amount of 750bn spent according to the same relative sacrifice and, then,

[2]We use GDP adjusted by purchasing power parity in order to account for difference in the price level of the EU countries

we consider the situation with a compensation of 500bn distributed according to that principle. We do so because, on the one hand, one can argue that the payments are to compensate for the Covid-19 damages, independent of how they are financed. In this respect, one would adopt a purely static view. On the other hand, one could argue that 250bn have to be paid back by the recipient countries in the future so that they have to cover that part of the damage by themselves, implying that it does not reduce losses.

Figure 1: EU Covid losses as ratio of GDP

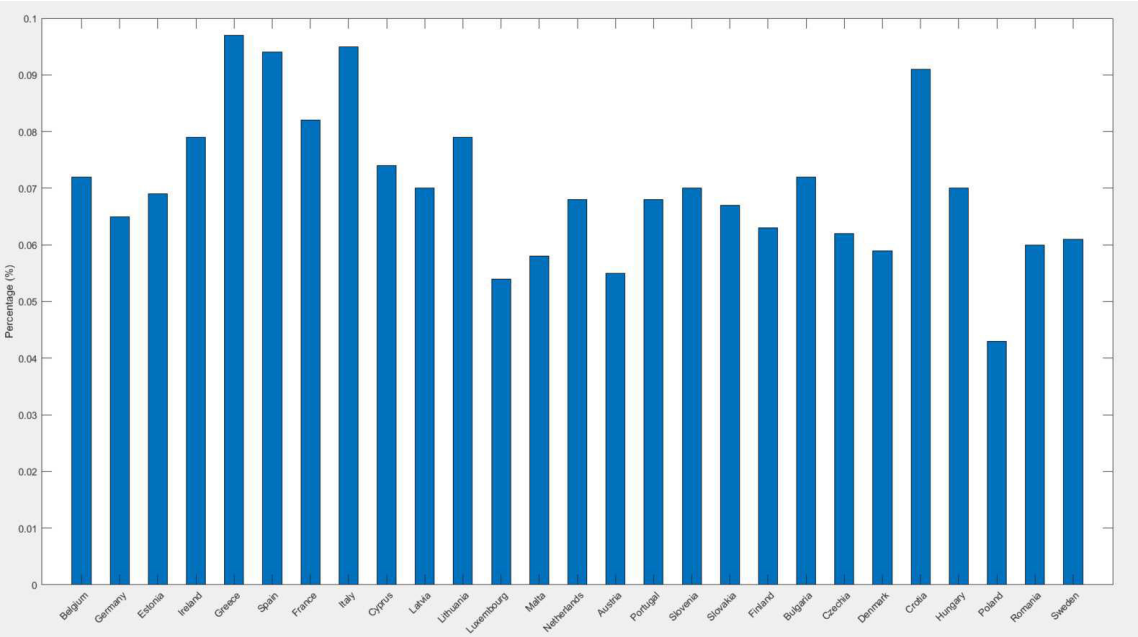


Table 1: Compensations and losses before ($L_i^v = -S_i^v$) and after ($L_i = -S_i$) compensation based on same proportional sacrifice principle.

Countries	Y_i^v	L_i^v/Y_i^v	Z=750bn		Z=500bn	
			Z_i	L_i/Y_i^v	Z_i	L_i/Y_i^v
Belgium	419.56	-0.072	21.82	-0.02	14.29	-0.04
Germany	3,121.08	-0.065	140.48	-0.02	84.44	-0.04
Estonia	34.49	-0.069	1.69	-0.02	1.07	-0.04
Ireland	292.05	-0.079	17.23	-0.02	11.99	-0.04
Greece	225.38	-0.097	17.36	-0.02	13.31	-0.04
Spain	1,331.08	-0.094	98.51	-0.02	74.61	-0.04
France	2,214.29	-0.082	137.31	-0.02	97.55	-0.04
Italy	1,784.95	-0.095	133.89	-0.02	101.84	-0.04
Cyprus	24.37	-0.074	1.32	-0.02	0.88	-0.04
Latvia	41.26	-0.070	2.06	-0.02	1.32	-0.04
Lithuania	71.33	-0.079	4.21	-0.02	2.93	-0.04
Luxembourg	50.36	-0.054	1.71	-0.02	0.81	-0.04
Malta	15.45	-0.058	0.59	-0.02	0.31	-0.04
Netherlands	692.93	-0.068	33.27	-0.02	20.83	-0.04
Austria	351.46	-0.055	12.31	-0.02	5.99	-0.04
Portugal	250.84	-0.068	12.04	-0.02	7.54	-0.04
Slovenia	56.86	-0.07	2.84	-0.02	1.82	-0.04
Slovakia	124.86	-0.067	5.87	-0.02	3.63	-0.04
Finland	189.77	-0.063	8.16	-0.02	4.75	-0.04
Bulgaria	114.76	-0.072	5.97	-0.02	3.91	-0.04
Czechia	304.27	-0.062	12.78	-0.02	7.32	-0.04
Denmark	233.17	-0.059	9.10	-0.02	4.91	-0.04
Croatia	81.66	-0.091	5.80	-0.02	4.33	-0.04
Hungary	222.35	-0.070	11.12	-0.02	7.13	-0.04
Poland	870.24	-0.043	20.03	-0.02	4.40	-0.04
Romania	418.73	-0.060	16.75	-0.02	9.23	-0.04
Sweden	384.51	-0.061	15.77	-0.02	8.86	-0.04

Computation of the losses $L_k = -S_k = (Z - S^v)\left(\frac{Y_k^v}{\sum_{i\in I} Y_i^v}\right),\ k = 1, \ldots, n$, and of the compensations $Z_k = Z\left(\frac{Y_k^v}{\sum_{i\in I} Y_i^v}\right) + S_k^v\left(\frac{\sum_{i\in I\setminus\{k\}} Y_i^v}{\sum_{i\in I} Y_i^v}\right) - \left(\frac{Y_k^v}{\sum_{i\in I} Y_i^v}\right)\left(\sum_{i\in I\setminus\{k\}} S_i^v\right),\ k = 1, \ldots, n$. GDP and compensations are expressed in billion of euros.

Table 1 presents the computation of the compensation payments using the concept of

the same proportional sacrifice with the results from the proposition 1. Recall that Y_i^v denotes the real GDP before the Covid-19 shock, S_i^v is the damage to real GDP caused by Covid-19, Z_i represents the compensation payment according to the same relative sacrifice principle, S_i gives damages after compensation and S_i/Y_i^v is the relative damage after compensation. In the table 1 we report losses, $L_i = -S_i$, in order to point out that these reduce the GDP in the economies under consideration. The compensation payments have been calculated such that all countries bear the same relative burden or damages according to the concept of the same proportional sacrifice. This is can be seen from table 1 (column 4 and column 6) considering a total compensation package of 750bn and 500bn, respectively. Further, in both instances the relative damages after compensation are equal for all countries as can be seen from columns 5 and 7 in table 1. Hence, the concept of the equal proportional sacrifice is fulfilled.

Table 2 provides an overview of our proposed compensation allocation relative to the real GDP before Covid-19. In other words, we computed the ratio of the compensation payments of individual countries to the real GDP before Covid-19. It can be observed that countries with higher GDP losses, such as Spain, Italy, Greece and France with a loss above 8%, receive compensations of more than 7% relative to their GDP in 2019. This is higher than the compensations for countries such as Denmark, Malta, Poland and Austria who experienced damages (losses) less than 6% of their GDP. Figure 2 gives a further graphical overview of the damages and of the compensations both as a percentage of GDP in 2019. It can be observed that the compensation payments for all individual countries relative to GDP in 2019 amounts to more than half of the damages relative to GDP in 2019. In the end the relative loss (damage) after the compensation package is the same for all countries. We can infer that this principle is therefore not discriminatory in the sense that all countries bear the same relative burden after the compensation package. Indeed, as opined by Neil (2000), the equal sacrifice principle can be considered as a formal characterization of fairness and as a fundamental concept of distributive justice.

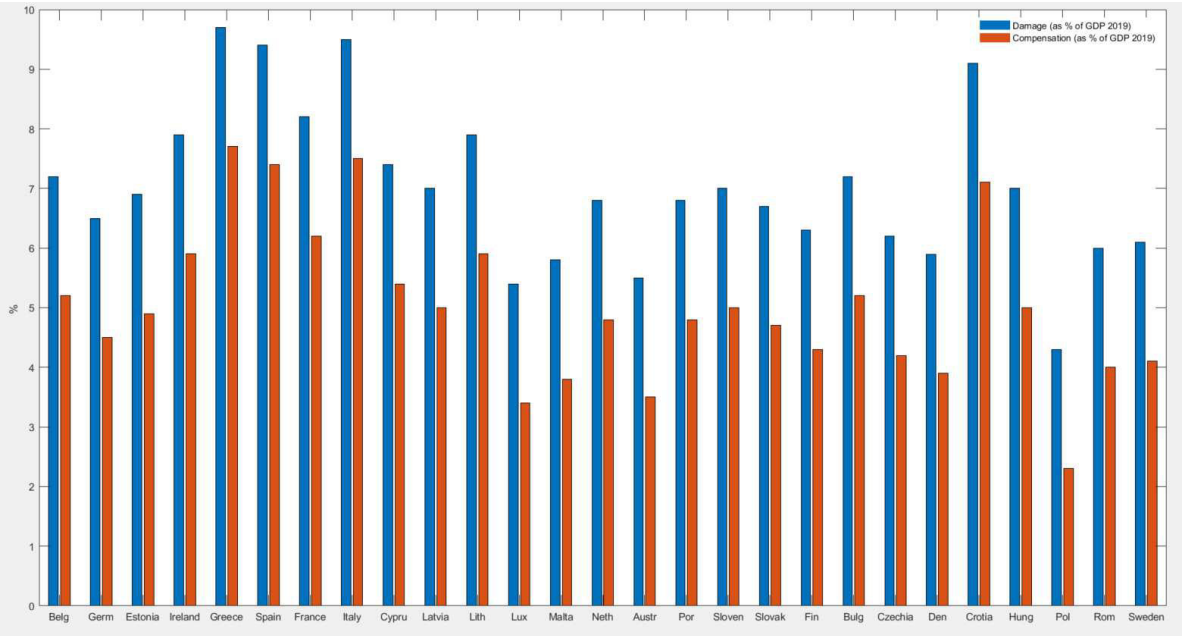
Next, we apply the concept of same absolute sacrifice to calculate the compensation recalling results from subsection 2.2. Table 3 presents the calculations of the compensation payments based on the concept of same absolute sacrifice for the case of 750bn compensation and of 500bn compensation payments, respectively. Loss per capita before compensation (l_k^v), loss per capita after compensation (l_k) and compensation per capita payments (z_k) have all been reported. Total compensations per country (in bns) have also been computed (Z_i) to show that the sum of all compensations for all countries adds up to the total of 750bn and of 500bn, respectively. Columns 4 and 7 both show per capita losses after compensation payments for the two scenarios and it can been seen that they are the same for all countries. Countries with higher per capita losses (column 2), notably Ireland, Luxembourg, Spain, France, Italy and Netherlands receive the highest compensations per capita (Column 3 and 6). Conversely, countries with low losses per capita such as Bulgaria and Poland receive the lowest compensations per capita. In the case of

Table 2: Compensation payments as percentage of GDP 2019 based on same proportional sacrifice principle.

Countries	Z=750bn		Z=500bn	
	Z_i	Z_i(%GDP)	Z_i	Z_i(%GDP)
Belgium	21.82	5.2%	14.29	3.4%
Germany	140.48	4.5%	84.44	2.7%
Estonia	1.69	4.9%	1.07	3.1%
Ireland	17.23	5.9%	11.99	4.1%
Greece	17.36	7.7%	13.31	5.9%
Spain	98.51	7.4%	74.61	5.6%
France	137.31	6.2%	97.55	4.4%
Italy	133.89	7.5%	101.84	5.7%
Cyprus	1.32	5.4%	0.88	3.6%
Latvia	2.06	5.0%	1.32	3.2%
Lithuania	4.21	5.9%	2.93	4.1%
Luxembourg	1.71	3.4%	0.81	1.6%
Malta	0.59	3.8%	0.31	2.0%
Netherlands	33.27	4.8%	20.83	3.0%
Austria	12.31	3.5%	5.99	1.7%
Portugal	12.04	4.8%	7.54	3.0%
Slovenia	2.84	5.0%	1.82	3.2%
Slovakia	5.87	4.7%	3.63	2.9%
Finland	8.16	4.3%	4.75	2.5%
Bulgaria	5.97	5.2%	3.91	3.4%
Czechia	12.78	4.2%	7.32	2.4%
Denmark	9.10	3.9%	4.91	2.1%
Croatia	5.80	7.1%	4.33	5.3%
Hungary	11.12	5.0%	7.13	3.2%
Poland	20.03	2.3%	4.40	0.5%
Romania	16.75	4.0%	9.23	2.2%
Sweden	15.77	4.1%	8.86	2.3%

500bn total compensation package, we notice that Poland and Bulgaria will not qualify for compensations (negative compensations) and would rather have to pay compensations to subsidize the other EU countries. We observe that the loss after compensation (column 7) is greater than the loss before compensation for these two countries. Hence, in a situation where the compensation package is not large enough, the principle of the same

Figure 2: Damage due to Covid-19 and compensation (as percentage of GDP 2019)



absolute sacrifice places countries with a low per capita loss at a disadvantage. In such a situation, the compensation package must be large enough to offset high per capita losses emanating from other economies. This goes to reinforce our argument that the principle of same proportional sacrifice dominates the principle of the same absolute sacrifice and should be adopted for the distribution of the Covid-19 compensation package.

4 Conclusion

In this note we have applied the concept of the same proportional sacrifice to determine the compensation payments to countries of an economic union that is hit by an asymmetric shock such that each country has to bear the same relative sacrifice after compensation. We have derived that the damage in each country, after the compensation, relative to the sum of damages equals the share of the country's GDP relative to the sum of the GDP of all economies. Then, we derived the compensation payment in a country and found that it equals the weighted difference of the total fund minus the weighted damages of all other countries plus that country's weighted damage. We applied our results to the allocation of resources from the 'Next Generation EU' program and computed the compensation each Member States receives, based on preliminary estimates as to the damages caused

Table 3: Compensations and losses before ($l_k^v = -s_k^v$) and after ($l_k = -s_k$) compensation based on same absolute sacrifice principle

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Countries	l_k^v	Z=750bn			Z=500bn		
		z_k	l_k	$Z_i(bn)$	z_k	l_k	$Z_i(bn)$
Belgium	-2,636.985	2,014.184	-622.801	23.074	1,454.68	-1,182.30	16.66
Germany	-2,443.656	1,820.855	-622.801	151.166	1,261.35	-1,182.30	104.72
Estonia	-1,796.067	1,173.266	-622.801	1.554	613.76	-1,182.30	0.81
Ireland	-4,704.539	4,081.738	-622.801	20.018	3,522.23	-1,182.30	17.27
Greece	-2,038.433	1,415.632	-622.801	15.182	856.13	-1,182.30	9.18
Spain	-2,665.726	2,042.925	-622.801	95.889	1,483.42	-1,182.30	69.63
France	-2,709.503	2,086.702	-622.801	139.836	1,527.20	-1,182.30	102.34
Italy	-2,809.342	2,186.542	-622.801	131.979	1,627.04	-1,182.30	98.21
Cyprus	-2,058.468	1,435.667	-622.801	1.257	876.16	-1,182.30	0.77
Latvia	-1,504.259	881.459	-622.801	1.692	321.96	-1,182.30	0.62
Lithuania	-2,016.742	1,393.942	-622.801	3.895	834.44	-1,182.30	2.33
Luxembourg	-4,429.908	3,807.107	-622.801	2.337	3,247.60	-1,182.30	1.99
Malta	-1,815.588	1,192.788	-622.801	0.589	633.28	-1,182.30	0.31
Netherlands	-2,726.451	2,103.650	-622.801	36.356	1,544.15	-1,182.30	26.69
Austria	-2,182.039	1,559.238	-622.801	13.813	999.73	-1,182.30	8.86
Portugal	-1,659.793	1,036.992	-622.801	10.657	477.49	-1,182.30	4.91
Slovenia	-1,912.655	1,289.855	-622.801	2.684	730.35	-1,182.30	1.52
Slovakia	-1,534.796	911.995	-622.801	4.971	352.49	-1,182.30	1.92
Finland	-2,166.636	1,543.835	-622.801	8.519	984.33	-1,182.30	5.43
Bulgaria	-1,180.351	557.550	-622.801	3.903	-1.95	-1,182.30	-0.01
Czechia	-1,771.341	1,148.541	-622.801	12.232	589.04	-1,182.30	6.27
Denmark	-2,369.428	1,746.627	-622.801	10.141	1,187.12	-1,182.30	6.89
Croatia	-1,822.993	1,200.193	-622.801	4.892	640.69	-1,182.30	2.61
Hungary	-1,592.656	969.855	-622.801	9.478	410.35	-1,182.30	4.01
Poland	-985.454	362.653	-622.801	13.771	-196.85	-1,182.30	-7.47
Romania	-1,294.068	671.267	-622.801	13.032	111.76	-1,182.30	2.17
Sweden	-2,292.742	1,669.941	-622.801	17.084	1,110.44	-1,182.30	11.36

Computation of the losses per capita $l_k = -s_k = -s/n,\ k = 1, \ldots, n$, and compensations per capita $z_k = s_k^v - s^v/n + z/n,\ k = 1, \ldots, n$.

by Covid-19.

Further, we used the principle of same absolute sacrifice to determine the compensation payments of the countries and showed empirically that this is not always plausible, especially in instances where the total compensation package is not large enough to offset high per capita losses from other countries in the union.

To finish our note we want to point out that our computations of the compensation hinges on the assumption that the economic capacity of a country depends only on its GDP. However, in reality it depends not only on GDP but also on its private and public wealth as well. Hence, in future works one could allow for that aspect by referring the damages to an aggregate of GDP and wealth that is to reflect the economic capacity of a country more accurately.

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A Proof of proposition 1

The concept of the same relative sacrifice implies

$$\frac{S_1}{Y_1^v} = \frac{S_2}{Y_2^v} = \ldots = \frac{S_n}{Y_n^v}$$

Setting $S_1/Y_1^v = S_2/Y_2^v$ and using $S_1 = S - \sum_{i=2}^{n} S_i$ leads to

$$S_2 = S\left(\frac{Y_2^v}{Y_1^v + Y_2^v}\right) - \sum_{i=3}^{n} S_i \left(\frac{Y_2^v}{Y_1^v + Y_2^v}\right), \tag{A.1}$$

where $S = \sum_{i=1}^{n} S_i$. Inserting S_2 from (A.1) in $S_2/Y_2^v = S_3/Y_3^v$ gives

$$S_3 = S\left(\frac{Y_3^v}{Y_1^v + Y_2^v + Y_3^v}\right) - \sum_{i=4}^{n} S_i \left(\frac{Y_3^v}{Y_1^v + Y_2^v + Y_3^v}\right)$$

Continuing this procedure, we obtain

$$S_{n-1} = S\left(\frac{Y_{n-1}^v}{\sum_{i=1}^{n-1} Y_i^v}\right) - S_n \left(\frac{Y_{n-1}^v}{\sum_{i=1}^{n-1} Y_i^v}\right) \tag{A.2}$$

Inserting S_{n-1} from (A.2) in $S_{n-1}/Y_{n-1}^v = S_n/Y_n^v$ and solving with respect to S_n, finally, leads to

$$S_n = S\left(\frac{Y_n^v}{\sum_{i=1}^{n} Y_i^v}\right) \tag{A.3}$$

Inserting S_n from (A.3) in (A.2) gives

$$S_{n-1} = S\left(\frac{Y_{n-1}^v}{\sum_{i=1}^{n} Y_i^v}\right) \tag{A.4}$$

and so on up to S_1. Noting that $S = S^v - Z$ leads to S_k in proposition.

To compute compensation payments Z_k, we note that $Z_k = S_k^v - S_k$ holds. Computing Z_n using (A.3) and $S = S^v - Z$, we obtain for country n

$$\begin{aligned} Z_n &= S_n^v - S_n^v \left(\frac{Y_n^v}{\sum_{i=1}^{n} Y_i^v}\right) - \sum_{i=1}^{n-1} S_i^v \left(\frac{Y_n^v}{\sum_{i=1}^{n} Y_i^v}\right) + Z\left(\frac{Y_n^v}{\sum_{i=1}^{n} Y_i^v}\right) \\ &= S_n^v \left(\frac{\sum_{i=1}^{n-1} Y_i^v}{\sum_{i=1}^{n} Y_i^v}\right) - \sum_{i=1}^{n-1} S_i^v \left(\frac{Y_n^v}{\sum_{i=1}^{n} Y_i^v}\right) + Z\left(\frac{Y_n^v}{\sum_{i=1}^{n} Y_i^v}\right) \end{aligned}$$

Proceeding in the same way to compute Z_{n-1} generates

$$Z_{n-1} = S_{n-1}^v \left(\frac{\sum_{i=1}^{n} Y_i^v - Y_{n-1}^v}{\sum_{i=1}^{n} Y_i^v}\right) - \left(\sum_{i=1}^{n} S_i^v - S_{n-1}^v\right)\left(\frac{Y_{n-1}^v}{\sum_{i=1}^{n} Y_i^v}\right) + Z\left(\frac{Y_{n-1}^v}{\sum_{i=1}^{n} Y_i^v}\right)$$

Continuing this procedure up to Z_1 demonstrates that Z_k is given by the expression in proposition. □

B Proof of proposition 2

The concept of the same absolute sacrifice implies

$$y_1^v - (y_1^v - s_1) = y_2^v - (y_2^v - s_2) = \ldots = y_n^v - (y_n^v - s_n) \leftrightarrow s_1 = s_2 = \ldots = s_n.$$

Using $s = \sum_{i=1}^{n} s_i$ shows that $s_k = s/n$ must hold.

Compensation payments per capita in each country are given by

$$z_k = s_k^v - s_k = s_k^v - \left(\frac{s}{n}\right) = s_k^v - \left(\frac{s^v - z}{n}\right),$$

where we used $s = s^v - z$. □