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Are there limits to robustness? Exploring tools from regenerative economics for a balanced transition towards a circular EU27

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ABSTRACT

The first step for transforming the current linear and degenerative socio-economic systems into ones that are circular and regenerative is to understand how they grow and develop. Here, we explore whether there are limits to robustness of a socio-economic system as the result of a linear metabolic structure, and how those limits could theoretically be affected by its transition to a circular economy. First, we study how the circular use of materials and the economic openness of the EU27 would affect the value of its circularity rate (as defined by Eurostat), theoretically. Then, given that the circularity rate does not capture regenerative aspects, we develop a conceptual framework based on regenerative economics and on indicators from ascendency analysis and ecological network analysis. We use this framework to assess a theoretical future case where the EU27 manages to successfully transition to a CE within its given linear material flow metabolism. The results show that there are limits to robustness, and which do not necessarily correspond to a maximum circularity rate. None of the 45 scenarios assessed can theoretically lead to the maximum robustness observed in natural ecosystems, including those which maximize the circularity rate. Interestingly, the highest possible robustness value is obtained at a circularity rate of about 33% as a combination of a material recovery rate of 30% and of a material export rate of 10%. Scenarios of higher circularity rate (as the result of higher export rates and/or higher material recovery rates) seem to lead to brittle networks. Other indicators from regenerative economics are also discussed. Furthermore, the results show that even if substantial steps are taken by the EU27 towards a circular economy, 100% circularity rate seems to be unlikely. This analysis highlights that the use of tools from regenerative economics can assist policy makers and researchers to account for and to monitor network properties such as those of resilience and robustness, during strategic planning activities for a transition to a regenerative circular economy.

1. Introduction

The hallmark reports *"Limits to growth"* (Meadows et al., 1972) and *"Our common future"* which is also known as the *"Brundtland report"* (World Commission on Environment and Development, 1987), have introduced environmental concerns in political agendas and set the scene for the global community to think of sustainability as a balancing act between the social, environmental, and economic dimensions. Fifty years later, at least four out of the nine identified planetary key ecosystems are operating outside a safe space for life on Earth, a fact pointing to a *"dangerous tendency for the world to move towards a global collapse scenario"* (United Nations Office for Disaster Risk Reduction, 2022). Evidently, the message of these reports is more relevant than ever, highlighting the urgency of taking collective actions against anthropogenic climate change and increasing social inequalities.

As a response to this challenge, the concept of a circular economy emerged and became popular particularly during the last decade. It is

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Abbreviationsand symbols

A	Ascendency or efficiency or ordered part (scaled)
APL	Average path length
c	Number of links
C	Capacity for development (scaled)
CE	Circular economy
CMR	Circular material use rate
DE	Domestic extraction of natural resources
DMC	Domestic material consumption
EXP_t	Exports (material, total)
EXP_w	Exports (material, waste)
FCI	Finn's cycling index
H	Capacity for development (unscaled)
H_c	Redundancy or overhead or resilience (unscaled)
IMP_t	Imports (material, total)
IMP_w	Imports (material, waste)
M	Degree of mutualism
N	Number of roles
R	Robustness
RCV_R	Amount of recovered materials
S	Degree of synergism
$U_{circular}$	Amount of circularly used materials
TST	Total system throughput
α	Degree of order
X	Average mutual information or efficiency or ordered part (unscaled)
Φ	Redundancy or overhead or resilience (scaled)

meant to change production and consumption patterns on a global level by encouraging societal stakeholders to adopt practices and circular business models which are based on the waste hierarchy principles (Geissdoerfer et al., 2020). Despite its multiple definitions (Kirchherr et al., 2017), the circular economy is most often described as an economy where waste and pollution are designed out, where materials and products are kept in use for as long as possible, and where socio-economic systems are not just restoring but also regenerating nature (Ellen MacArthur Foundation, 2019). Like every concept, the circular economy has been critiqued (Corvellec et al., 2021), and its limitations made it clear that it should not be seen as a universal remedy (Wijkman, 2021). It is often believed that the adoption of circular systems will have a positive effect in terms of environmental impacts, but this might not always be the case meaning that circular business models should be well-thought through during the design phase to ensure that they will become inherently restorative and regenerative of nature (Salvador et al., 2020).

The regenerative aspect, particularly, is often overlooked or addressed only qualitatively, as a *"symbolic/evocative term with little practical application in the context of circular systems except in the case of certain agricultural practices"* (Morseletto, 2020a). It is only recently that discussions around the transition to a circular economy are becoming more concerned in addressing explicitly the concept of regeneration.

If the circular economy is indeed a way towards a society for inclusive prosperity which respects planetary boundaries and covers social needs, then the first step for transforming the current linear and degenerative socio-economic systems into ones that are circular and regenerative should be to understand how they grow and develop. To seek such knowledge is both intuitive and imperative since the establishment of systems which cannot renew themselves will be by default unsustainable.

Regenerative economics (RE) is a relatively new scientific field which offers tools for understanding the regenerative aspects of our economy. Its theories and methods build on ecological concepts such as those of ecological succession and the adaptive cycle (Burkhard et al., 2011; Fath et al., 2015). These describe how natural ecosystems (and by conjecture, also socio-economic systems) grow and develop by capturing, retaining, and recycling natural resources and energy in their networks where *"cycling at one scale is structural storage at another"* (Fath et al., 2001). In RE, the sun and Earth are recognized as principal and original capital assets where natural capital and ecosystem services cannot be substituted by human-made capital, which is in fact the foundational reasoning behind a strong sustainability perspective. Under this light, natural ecosystems are seen as the embodiments of sustainability since they have existed for millennia. Ultimately, RE is concerned with expanding knowledge related to the development rather than growth of socio-economic systems, by following a transdisciplinary approach to study and foster the creation of robust socio-economic systems (Goerner et al., 2009; Kharrazi et al., 2017; Kharrazi and Masaru, 2012; Lietaer, 2010; Lietaer et al., 2010; Ulanowicz et al., 2009) which can *"flourish within limits to growth"* (Jørgensen et al., 2015).

Interestingly, healthy natural ecosystems which have been studied in this regard, were found to balance between a certain proportion of efficiency in streamlining resources and of redundancy in their connections for resilience (Ulanowicz, 2009; Zorach and Ulanowicz, 2003). This balance is theorized to endow natural ecosystems with maximum robustness which led to naming this operating space as the *"window of vitality"* (Ulanowicz, 2009; Zorach and Ulanowicz, 2003).

So far, studies on the robustness of socio-economic networks seem to be inconclusive about where they balance across the spectrum of possibilities, and whether they fall within the *"window of vitality"*. On one hand, socio-economic systems have been found to obtain low robustness values due to excessive redundancy in their network connections as the result of *"hidden flows"* within products or services which circulate in the system (Scharler et al., 2018). Similar outcomes were obtained when these systems were examined sector-wise in networks that were more interlinked rather than metabolically sequential (Kharrazi et al., 2013). On the other hand, it has been argued that socio-economic systems have low robustness values due to a persistent focus on optimizing resource use efficiencies to maximize financial gains by relying on a monetary monopoly (Lietaer, 2010).

There are also voices suggesting that it is *"possible for various human and semi-human built networks to occupy both spectrums of high degree of order and high degree of redundancy or resilience"* (Tumilba and Yarime, 2015). A similar reasoning has been proposed for natural ecosystems (and perhaps as a conjecture also for socio-economic systems) stating that sustainable ecosystems could be located elsewhere, away from the *"window of vitality"* (Ulanowicz, 2020). To explore this latter possibility, a recent study on the material and energy flows within the EU27 by using Eurostat data showed that these occupied a *"window of efficiency"* where their low robustness values were mainly due to their linear network structures given that they were analyzed as sequential socio-economic metabolic processes (Zisopoulos et al., 2022). The finding is in line with Fath et al. (2019a,b) who hypothesized that "*more linear networks (more like chains rather than webs) will plot to the right of the curve peak, since vertical integration prunes redundant connections"*.

So far, and to the best of the authors' knowledge, no study examined the potential limitations on the robustness of a socio-economic systems which strive to maximize their circulation of resources. Therefore, the aim of this study is to explore whether there are limits to robustness as the result of a linear metabolic structure, and how those limits could theoretically be affected by transitioning to a circular economy. To this end, we apply ascendency analysis and ecological network analysis on the material flow metabolism of the EU27 by using data from Eurostat. More specifically, we conduct a parametric analysis on the circularity rate (or circular material use rate) indicator by varying the values of two key variables: the material recycling rate and the export rate. The hypothesis then is stated as follows: if the circularity rate (as defined by Eurostat) would be maximized theoretically then the circular economy of the EU would be a regenerative one (as described by indicators from regenerative economics). To examine this hypothesis, we formulate two research questions:

1. By assuming that the EU undertakes substantial steps towards a CE, which combinations (scenarios) of circular use of materials (as captured by the material recovery rate) and of economic openness (as captured by the export rate of materials) would maximize the circularity rate indicator, theoretically and what would these results imply for the European economy?
2. Which of these scenarios would lead to a regenerative European economy (as captured by indicators from regenerative economics)?

In Section 2 we present the main drawbacks of the circularity rate indicator, we provide the theoretical underpinning of RE, and we present a conceptual framework which brings together the dimension of circularity and of regeneration to organize the study. In Section 3 we formalize the parametric analysis of the CMR indicator by listing the assumptions describing optimal conditions for achieving a CE in the EU27, and we present two quantitative methods from RE (ascendency analysis and ecological network analysis). In Section 4 we answer the research questions, and in Section 5 we conclude.

2. Theoretical background

2.1. Tools from regenerative economics

RE stems from ecological economics as a cross-pollination between the scientific fields of information theory and ecosystems ecology. The former provides quantitative methods and concepts such as information entropy [i.e., the average level of information, surprise, or uncertainty inherent to a variable's possible outcomes (Ulanowicz, 2009)] whereas the latter explores how energy and resources flow through natural ecosystems (Fath et al., 2019). Two of its well-established quantitative methodologies are ascendency analysis and ecological network analysis.

2.1.1. Ascendency analysis

One important method which can be used to quantify network properties related to an ecosystem's health is ascendency analysis where system growth and system development are two distinctive yet important counterparts of natural ecosystems (Ulanowicz, 2009). On the one hand, system growth (often termed as total system throughput) relates more to the total activity of resources which flow through the ecosystem. In economic systems, growth is analogous to a country's gross domestic product which, however, cannot distinguish speculative bubbles and unhealthy growth from regenerative re-investments (Lietaer et al., 2010; Fath et al., 2019a,b). On the other hand, system development refers to an ecosystem's ability to balance between two complementary network properties: a) its network efficiency in channeling the resource flows of interest via its network and b) its resilience to shocks by diverting flows through an excessive number of pathways, a redundancy which is seemingly obsolete but invaluable as a buffer and *"cache"* for future system development (Fath, 2017; Ulanowicz et al., 2009).

In this context, network efficiency refers to how well the circulating medium is streamlined throughout the network of interest (known as the *"degree of order"* of the system) as opposed to other expressions of efficiency which are typically defined as ratios of total useful output over total input consumed (Panyam and Layton, 2019a). Resilience is related to the capability of a natural ecosystem to navigate across all four stages of the adaptive cycle (i.e., growth, conservation, collapse, and reorganization) and maintaining its position during a shock by investing in sufficient redundancy and modularity in its connections between the network compartments or nodes (Fath et al., 2015; Fath et al., 2019).

2.1.2. Ecological network analysis

Another important method in RE is ecological network analysis which allows for the calculation of other network properties such as the degree of indirect effects of flows, the degree of mutualism, and the degree of synergy. Instead of just examining the interactions between the nodal compartments of a network in a pairwise manner, indirect effects account for *"the entire path traced by the energy-matter through the network from boundary input, through system nodes, to boundary output"* and *"measures how much of the total flow through a node (and summed for all nodes in the system) originates from distal sources"* highlighting *"the role that non-direct flow contributes to the overall flow pattern in the network"* (Burkhard et al., 2011). Interestingly, indirect effects can be dominating in ecosystem networks an effect known as *"network non-locality"* and which is thought to have a positive impact (Fath, 2012). The degree of mutualism and the degree of synergism show when the overall relationships across the different compartments of an ecosystem's network are more positive than negative in a qualitative or quantitative way, respectively (Burkhard et al., 2011).

2.1.3. Other indicators

Other important indicators include Finn's Cycling Index (*FCI*) and the average path length (*APL*) also known as network aggradation. According to Nielsen et al. (2019) *"network aggradation processes generate maximum intrasystem throughflows at steady state"* moving the system away from thermodynamic equilibrium and increasing its complexity. *FCI* is analogous to the multiplier effect in economics, indicating *"the proportion of total system throughflow of energy or matter that is generated by cycling"* (Ma and Kazanci, 2014), whereas *APL* shows the ability of an ecosystem to generate flow activity per unit of given boundary input (Fath et al., 2019). For a more comprehensive explanation of the theories, methods, and indicators used here, along with their limitations, the reader is referred to relevant literature (Fath, 2015, 2017; Fath and Scharler, 2018; Fath et al., 2019a,b).

2.2. Monitoring the transition to the circular economy in the EU

In 2015, the European Commission has put forward its first Action Plan to transition to a circular economy (CE) by promoting sustainable consumption, by ensuring that waste is prevented, and that primary and secondary resources used are better managed and kept in the European economy for as long as possible (European Commission, 2015). In its second action plan published in 2020, the European commission stressed the importance of regeneration by defining the CE as a *"regenerative growth model that gives back to the planet more than it takes"* (European Commission, 2020). All Member States have been encouraged by the European Commission to adopt or to update their national CE strategies, and all EU institutions and bodies have been invited to endorse and actively contribute to this plan via several implementation actions. Examples of implementation actions include (but are not limited to) setting waste reduction targets, and developing policy frameworks, directives, and regulatory measures (such as extended responsibility schemes). Those are intended to foster, for example, the *"right to repair"* and the design of products for energy efficiency, durability, reparability, upgradability, maintenance, reuse, and recycling (European Commission, 2020).

Acknowledging the multifaceted and complex aspects of CE, the European Commission developed a framework with indicators to capture aspects related to production and consumption, waste management, secondary raw materials, competitiveness, and innovation to monitor progress towards a CE both on a national and on a European level. A recent econometric study[1] examined Eurostat data on these indicators and found that: a) the higher the GDP of a Member State the higher the municipal generation *per capita*, b) the higher the use of secondary raw materials the lower the municipal waste generation, and c) the higher the number of patents in a CE the higher the GDP generation (Grdic et al., 2020). Based on their findings, the authors proposed that *"the CE concept can ensure economic growth and GDP growth while reducing the use of natural resources and ensuring greater environmental protection"* (Grdic et al., 2020). However, the European Economic and Social Committee argued that the narrow definition of CE should be developed further with more indicators for which the lack of data should not be a reason of exclusion, but their gaps should be made explicit and filled strategically since the use of traditional old data *"will not be accurately measuring the transition to a new economic model"* (European Economic and Social Committee, 2018).

2.3. The drawbacks of circularity rate as an indicator

The circularity rate or material use rate (CMR) indicator which is also known as circularity rate, even though it is certainly not the only indicator which is intended to describe progress towards a CE, it is one of the most popular ones representing the share of materials which are fed back to the economy (Fig. 1). It is relevant for reporting purposes particularly for the sufficient provision of secondary raw materials in the European economy.

Whereas the CMR indicator is useful as a percentage, it focuses only on the fraction of materials that are returned to the European economy, and the underlying reasons which could affect its numerical value can be misleading if not made transparent. For example, the circularity rate of the EU27 increased from 8.3% in 2004 to 12.8% in 2020 (European Commission, 2021). However, at least for the period between 2004 and 2016, research suggests that this increase should be attributed mainly to a relatively large reduction in the domestic material consumption rather than to the modest and fluctuating effects of recycling activities (Chioatto and Sospiro, 2021).

Below we list drawbacks of the CMR indicator which need to be addressed for an informed and transparent transition towards CE. The CMR indicator:

- is **insensitive to the techno-economic status** of different Member States and to the behavioral aspects (consumption patterns) of citizens. For example, when looking at Eurostat data for 2018[2] (European Commission, 2021; Eurostat, 2021e, 2021f), one can see that Sweden, a country with a substantially high GDP (43,760 euros/capita) and considerable amount of waste generation (13,628 kg/capita), achieved almost the same circularity rate (approximately 7%) with Hungary which, during that year, had a much lower GDP (12,690 euros/capita) but also much more modest in its waste generation (1,879 kg/capita).
- it **does not distinguish between the sustainable and unsustainable re-introduction of *"circular"* materials** to the European economy which is particularly important for two reasons. Firstly, because, even though the most frequently used targets are related to the recovery and recycling of materials, they *"do not necessarily promote a CE because recovery and recycling activities destroy products' integrity and do not help products remain in the economy"* (Morseletto, 2020b). Secondly, because CE practices should not be considered as *"sustainable"* by default (Schaubroeck, 2020).
- it **accounts only for material flows on national or European scales**, but it does not say anything about prolonging or extending the life cycle of products and materials (Pacurariu et al., 2021), about the embodied material and energy content, the consumption of non-renewable sources, and the environmental impact (e.g., toxicity and global warming potential amongst others) these flows might bear, about the reintroduction of critical raw materials (and therefore degree of independence), about circularity at the regional or local level, or about resilience and regenerative aspects.

2.4. Conceptual framework

Here, we develop a conceptual framework (Fig. 2) which is composed of two dimensions describing the transition of an economy from a linear into a circular one either in a regenerative or a degenerative way. The *"business as usual"* quadrant represents the status quo i.e., a linear economy which is extractive, exploitative, and dependent of non-renewable natural resources. The upper left quadrant assumes a weak sustainability point of view which leaves room for the possibility of future technological advances to restore and regenerate natural capital. The bottom right quadrant captures the possibility of transitioning to a sustainable dystopia, a world of degenerative linear operations which have been rebranded as circular. Finally, at the top right quadrant is a healthy circular economy which is envisioned to be robust, mutualistic, and synergistic based on the principles of regenerative economics. We use this framework as a general guide to examine the relationship between each one of the selected indicators from regenerative economics with the circularity rate indicator (as described by Eurostat).

3. Materials & methods

3.1. Parametric analysis of the circular material use rate

The values of the *CMR* indicator (European Commission, 2021) are calculated with equation (1) on data of material flows which are visualized in the form of a Sankey diagram (Fig. 3):

$$CMR = \frac{U_{circular}}{M_{overall}} = \frac{RCV_R - IMP_W + EXP_W}{DMC + RCV_R - IMP_W + EXP_W} \tag{1}$$

where $U_{circular}$ is the amount of materials that are used in circular ways within an economy, $M_{overall}$ is the overall use of materials, RCV_R is the amount of materials that are recovered by *"any operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes, and includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations"* (European Commission, 2021), IMP_W and EXP_W are the amounts of imported and exported waste for recycling purposes, respectively, and *DMC* is the domestic material consumption given by equation (2):

$$DMC = DE + IMP_t - EXP_t \tag{2}$$

where *DE* is the domestic extraction of natural resources, and IMP_t and EXP_t are the amounts of total imports and total exports, respectively. All terms mentioned (except *CMR* which is a ratio) have the units of Gt/year.

3.2. Assumptions and construction of scenarios

We examine a theoretical future case where the EU27 manages to successfully transition to a CE by assuming the following. Given these assumptions we conduct a parametric analysis of the *CMR* indicator (equation (3)) for 45 different scenarios (Fig. 4) as combinations of the

[1] The authors stated that *"increasing GDP per capita by 1% would mean an average increase of around 44.33 EUR Value-added Mio, 1.*04 kg *waste per capita, 0.1555% in the recycling rate of municipal waste, around 0.05% in the recycling rate of packaging waste, around 0.*5 kg *per capita in the recycling of bio-waste, and 0.06% in the recycling rate of e-waste"* (Grdic et al., 2020).

[2] Compared to the EU27 average with a GDP of 27,620 euros/capita, waste generation of 5,237 kg/capita, and a circularity rate of 11.7% (European Commission, 2021; Eurostat, 2021a, 2021b).

Fig. 1. Monitoring framework for the CE of EU27 (Eurostat, 2021d). The interested reader is referred to the website of Eurostat for more details on the monitoring framework and its indicators (link available in the previous reference).

recycling rate RCV_R and export rate EXP_t.

1. The total inflow of processed materials for all scenarios besides scenario 1 which represents the situation in 2019, is constant at 8.08 Gt/year. This constraint describes a situation where the EU27 **does not grow in terms of total input material flows.**
2. There is a constant total import rate (IMP_t) of 10% or 0.8 Gt/year. This constraint describes a situation where the EU27 becomes **more self-sufficient** by improving its internal circular processes and therefore becoming less dependent on other countries.
3. There are no waste imports (IMP_w) and no waste exports (EXP_w). This constraint describes a situation where the EU27 **manages to close its waste material flows within its borders** effectively, and where the circular use of materials is fully captured by the recycling rate (RCV_R) representing the establishment of *"a strong and coherent product policy framework that will make sustainable products services and business models the norm and transform consumption patterns so that no waste is produced in the first place"* including actions from the European Commission that *"aim to ensure that the EU does not export its waste challenges to third countries"* and which *"contribute to making "recycled in the EU" a benchmark for qualitative secondary materials"* (European Commission, 2020).
4. There is **no backfilling.** This constraint describes a situation where the EU27 manages to redirect waste streams of backfilling practices (i.e., *"recovery operations where suitable waste is used for reclamation purposes in excavated areas or for engineering purposes in landscaping and where the waste is a substitute for non-waste materials"* (Eurostat, 2021c)) towards other useful purposes.

To conduct the ascendency analysis and ecological network analysis, the Sankey diagram presented in Fig. 3 is transformed into a network shown in Appendix A. We follow the recommendation of Chatterjee

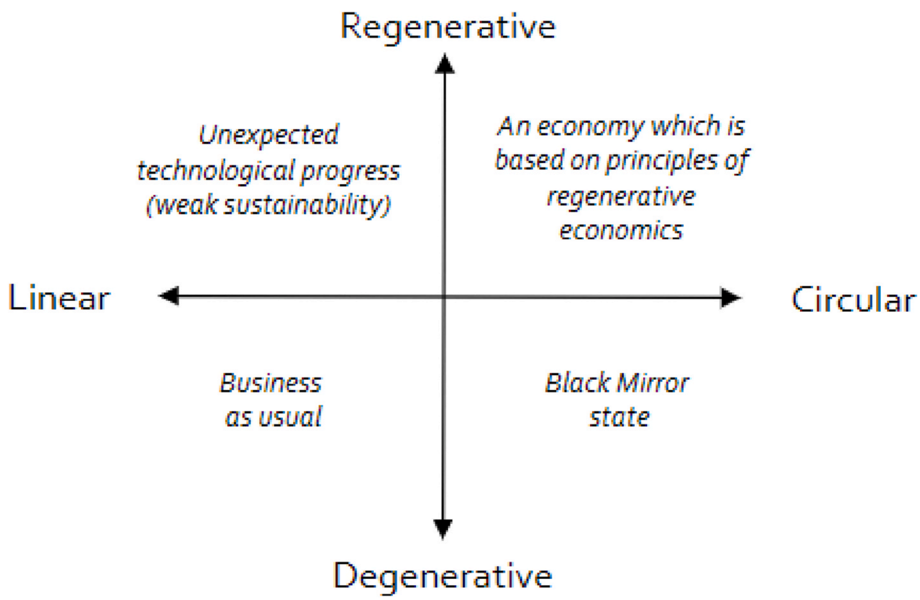

Fig. 2. Theoretical framework which describes four different future possible scenarios using two dimensions showing: a) whether the system of interest is linear or circular as described by Eurostat, and b) whether the system of interest is degenerative or regenerative as described by indicators from RE (Fath et al., 2019a,b).

et al. (2021) who suggested that processes which play essential roles in a system's function, and which possess a certain level of independence, are to be modelled as nodes. Therefore, we treat the following processes as additional nodes: *"imports of waste for recycling"*, *"imports excluding imports of waste for recycling"*, *"exports of waste for recycling"* and *"exports excluding exports of waste for recycling"*. All relevant flows and mass balances for the scenarios are calculated via the equations shown in Appendix B which are based on the obtained data from Eurostat for 2019 (scenario 1), they assume some proportionality for some flows (e.g., for *"dissipation"*, *"waste landfilled"*, and *"incineration"*), and are adjusted accordingly for the recycling and export rates per scenario.

3.3. Ascendency analysis

First, we convert the material flow data into a matrix form to conduct all following calculations. A material flow from node i to node j is symbolized with T_{ij} (Gt/year). Then, we calculate the total system throughput (Gt/year):

$$T_{..} = TST_{..} = \sum_{j=1}^{n} z_j + \sum_{j=1}^{n}\sum_{j=1}^{n} T_{ij} + \sum_{i=1}^{n} y_i \tag{3}$$

The total internal flow system throughput (Gt/year) is:

$$TST_{flow} = \sum_{j=1}^{n}\sum_{j=1}^{n} T_{ij} \tag{4}$$

The capacity of the network for development (bits) is:

$$H = -\sum_{i,j}\left(\frac{T_{ij}}{T_{..}}\right)\log_2\left(\frac{T_{ij}}{T_{..}}\right) \tag{5}$$

The average mutual information of the network (bits) is:

$$X = \sum_{i,j}\left(\frac{T_{ij}}{T_{..}}\right)\log_2\left(\frac{T_{ij}}{T_{i.}}\frac{T_{..}}{T_{.j}}\right) \tag{6}$$

The redundancy or resilience of the network (bits) is:

$$H_c = -\sum_{i,j}\left(\frac{T_{ij}}{T_{..}}\right)\log_2\left(\frac{T_{ij}^2}{T_{i.}T_{.j}}\right) \tag{7}$$

The capacity of the network to develop is the sum of its ordered and disordered part:

$$H = X + H_C \tag{8}$$

Scaling these three properties with $T_{..}$ the units become Gt bits/year:

$$A = T_{..}X \tag{9}$$

$$\Phi = T_{..}H_c \tag{10}$$

$$C = A + \Phi \tag{11}$$

The degree of order of the network is:

$$a = \frac{X}{H} \tag{12}$$

The robustness of the network is

$$R = -\alpha\ln(\alpha) \tag{13}$$

By plotting the degree of order with the robustness it is possible to construct a robustness curve to identify whether the network under study is more brittle, more redundant, or whether it is near the *"window of vitality"*. This window is a range of degrees of order which describe the state of healthy (i.e., sustainable) natural ecosystems as a specific balance between network efficiency in streamlining resources and sufficient redundancy in network connections for resilience. This range is back-calculated with equations which are used for calculating the indicators *"number of roles"* and *"number of links"*. This is done by using their corresponding upper and lower values which have been observed for various natural ecosystems. The *"window of efficiency"* has been proposed for socio-economic systems such as the material and energy flow networks of the EU27 between 2010 and 2018 (Zisopoulos et al., 2022).

The number of roles is:

$$n = 2^X \tag{14}$$

The number of links or link density is:

$$c = 2^{\left(\frac{H_c}{2}\right)} \tag{15}$$

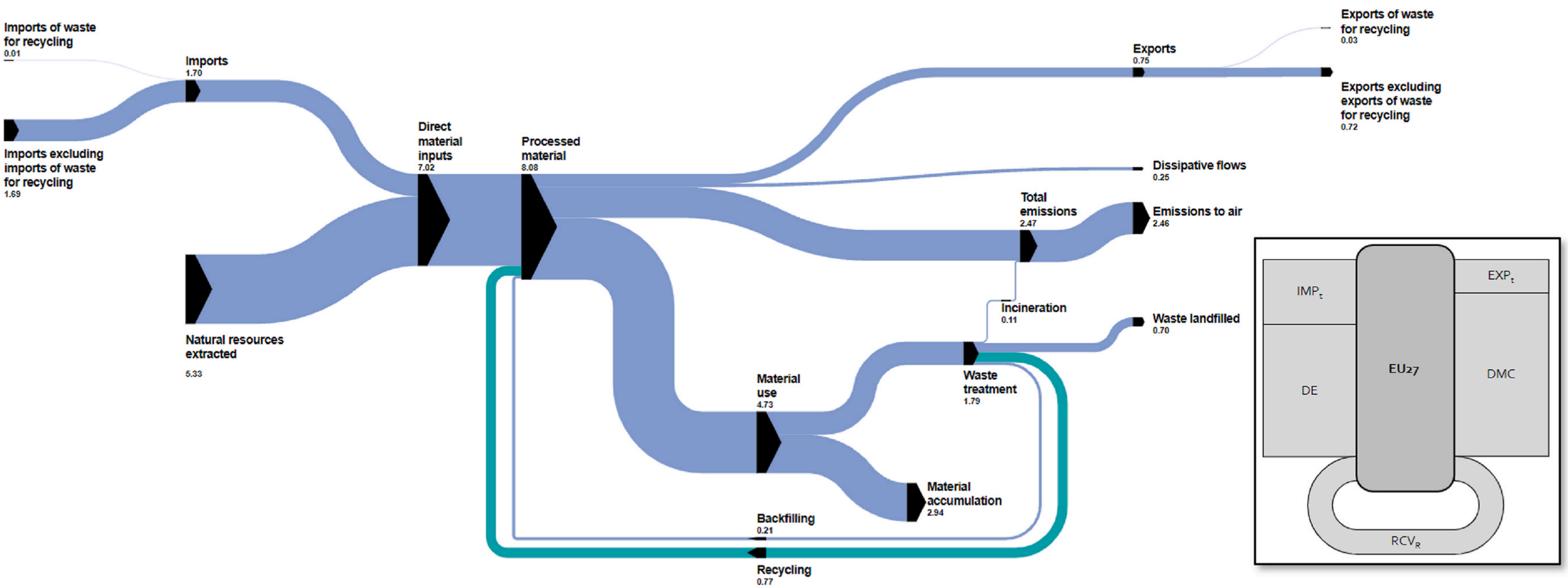

Fig. 3. *Left:* Material flow diagram (Sankey diagram) for the European Union (27 countries) in 2019 in Gigatonnes (Gt). Figure and data accessed on the September 28, 2021 (Eurostat, 2021b). *Right:* Simplified version of the Sankey diagram used for the parametric analysis where IMP_t is the total material imports rate, DE is the domestic extraction of natural resources rate, EXP_t is the total material exports rate, DMC is the domestic material consumption rate, and RCV_R is the recycling rate.

Scenarios		EXP$_t$									
		9,2%	20%	30%	40%	50%	60%	70%	80%	90%	100%
RCV$_R$	9,5%	1	2	3	4	5	6	7	8	9	
	20%	10	11	12	13	14	15	16	17		
	30%	18	19	20	21	22	23	24			
	40%	25	26	27	28	29	30				
	50%	31	32	33	34	35					
	60%	36	37	38	39						
	70%	40	41	42							
	80%	43	44								
	90%	45									
	100%										

Fig. 4. Scenarios expressed as different combinations of the material recovery rate (RCV_R) and of the export rate of materials (EXP_t). The number in each square represents the scenario studied.

3.4. Ecological network analysis

First, we normalize all elements of the original data matrix to create a new matrix G which is known as the direct flow intensity matrix with elements g_{ij}:

$$G = (g_{ij}) \tag{16}$$

$$g_{ij} = \frac{T_{ij}}{\sum_{i=1}^{n} T_{ij} + z_i} \tag{17}$$

These elements represent the directly measurable flows (or probabilities of flow) between two nodes i and j. To calculate the indirect flows in the network we raise matrix G consecutively to n powers and we sum all the generated matrixes. The elements of each new matrix that is generated represent the probability of the flows to reach other nodes in the network in n steps. The new matrix which is created is called the integral flow matrix N with elements n_{ij}:

$$N = (n_{ij}) = G^0 + G^1 + G^2 + \ldots G^n = (I - G)^{-1} \tag{18}$$

Then we can calculate the indicator DI which shows whether there is dominance of indirect effects:

$$DI = \frac{\sum_{i,j=1}^{n} (n_{ij} - g_{ij} - \delta_{ij})}{\sum_{i,j=1}^{n} g_{ij}} \tag{19}$$

where δ_{ij} is a binary variable taking the value of one when there is a connection between node i and node j, and zero otherwise.

Using again the matrix with the original dataset we can normalize its elements to construct another matrix, the direct utility flow matrix D:

$$D = (d_{ij}) \tag{20}$$

$$d_{ij} = \frac{T_{ij} - T_{ji}}{\sum_{i=1}^{n} T_{ij} + z_i} \tag{21}$$

Following a similar procedure, we can raise this matrix to n powers, and sum the generated matrixes to create the matrix U with elements u_{ij}:

$$U = (u_{ij}) = D^0 + D^1 + D^2 + \ldots D^n = (I - D)^{-1} \tag{22}$$

This matrix can be used to construct new matrixes the elements of which are not numerical values but signs which indicate whether a flow is directed from node i to node j or vice versa. Using these signs, a new matrix can be created which summarizes the interrelations between two nodes. There are four different combinations of signs which describe different types of relationships between the nodes: mutualistic (+,+), exploitative (+,-), exploited (-,+), and competitive (-,-). These matrixes can be used to calculate the degree of mutualism M and degree of synergism S:

$$M = \frac{S_+}{S_-} = \frac{\sum max[sgn(u_{ij}), 0]}{-\sum min[sgn(u_{ij}), 0]} \tag{23}$$

$$S = \frac{\sum max(u_{ij}, 0)}{-\sum min(u_{ij}, 0)} \tag{24}$$

3.5. Other indicators

To calculate FCI we first need to calculate the total system throughput which cycles through the nodes:

$$TST_{ci} = \frac{(n_{ii} - 1)}{n_{ii}} T_i \tag{25}$$

$$FCI = \frac{\sum TST_{ci}}{TST_{flow}} \tag{26}$$

The average path length APL which is also known as network aggradation, is calculated as follows:

CMR	IMP$_t$	EXP$_t$																			
DE	DMC	9,2%		20%		30%		40%		50%		60%		70%		80%		90%		100%	
RCV$_R$	9,5%	11%	1,70	13%	0,81	14%	0,81	17%	0,81	20%	0,81	25%	0,81	33%	0,81	50%	0,81	100%	0,81		
		5,33	6,28	6,47	5,66	6,47	4,85	6,47	4,04	6,47	3,23	6,47	2,43	6,47	1,62	6,47	0,81	6,47	0,00		
	20%	22%	0,81	25%	0,81	29%	0,81	33%	0,81	40%	0,81	50%	0,81	67%	0,81	100%	0,81				
		5,66	5,66	5,66	4,85	5,66	4,04	5,66	3,23	5,66	2,43	5,66	1,62	5,66	0,81	5,66	0,00				
	30%	33%	0,81	38%	0,81	43%	0,81	50%	0,81	60%	0,81	75%	0,81	100%	0,81						
		4,85	4,85	4,85	4,04	4,85	3,23	4,85	2,43	4,85	1,62	4,85	0,81	4,85	0,00						
	40%	44%	0,81	50%	0,81	57%	0,81	67%	0,81	80%	0,81	100%	0,81								
		4,04	4,04	4,04	3,23	4,04	2,43	4,04	1,62	4,04	0,81	4,04	0,00								
	50%	56%	0,81	63%	0,81	71%	0,81	83%	0,81	100%	0,81										
		3,23	3,23	3,23	2,43	3,23	1,62	3,23	0,81	3,23	0,00										
	60%	67%	0,81	75%	0,81	86%	0,81	100%	0,81												
		2,43	2,43	2,43	1,62	2,43	0,81	2,43	0,00												
	70%	78%	0,81	88%	0,81	100%	0,81														
		1,62	1,62	1,62	0,81	1,62	0,00														
	80%	89%	0,81	100%	0,81																
		0,81	0,81	0,81	0,00																
	90%	100%	0,81																		
		0,00	0,00																		
	100%																				

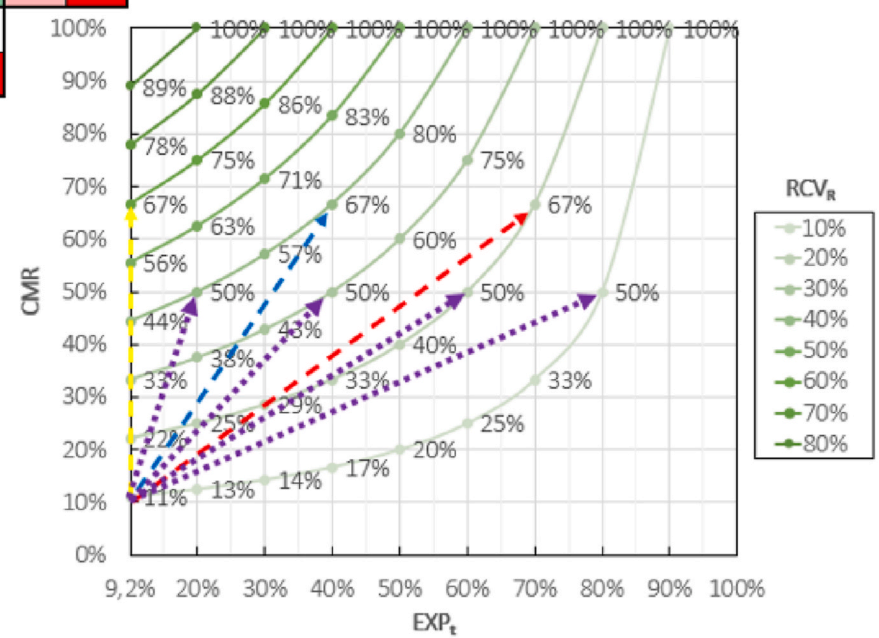

Fig. 5. Circular Material Use Rate (*CMR*) or circularity rate as a function of the total export rate (EXP_t) and of the material recovery rate (RCV_R) both in the form of a table and of a graph. The point of origin of all arrows within the orange box represents the situation of the EU27 in 2019 as shown in Fig. 3: i.e., Processed Material = 8.08 Gt/year, IMP_t = 1.7 Gt/year (21% of Processed Material), *DE* = 5.33 Gt/year, *DMC* = 6.28 Gt/year, EXP_t = 0.75 Gt/year (9.2% of Processed Material), RCV_R = 0.77 Gt/year (9.5% of the total Processed Material flow), backfilling = 0.21 Gt/year, IMP_w = 0.01 Gt/year, EXP_w = 0.03 Gt/year. The rest of the elements inside the matrix: a) for the first row, were calculated at an RCV_R of 10% (instead of 9.5%), and b) for the first column, they were calculated at an EXP_t of 10% (instead of 9.2%). The blue, red, and yellow arrows indicate three theoretical transition directions towards future states as combinations of RCV_R and IMP_t which could lead from a *CMR* of 11% (achieved in 2019) to a *CMR* of 67% given Equation (1) and the assumptions stated under Section 2. The purple arrows indicate four different theoretical transition directions towards future states which could lead from a *CMR* of 11%–50%. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

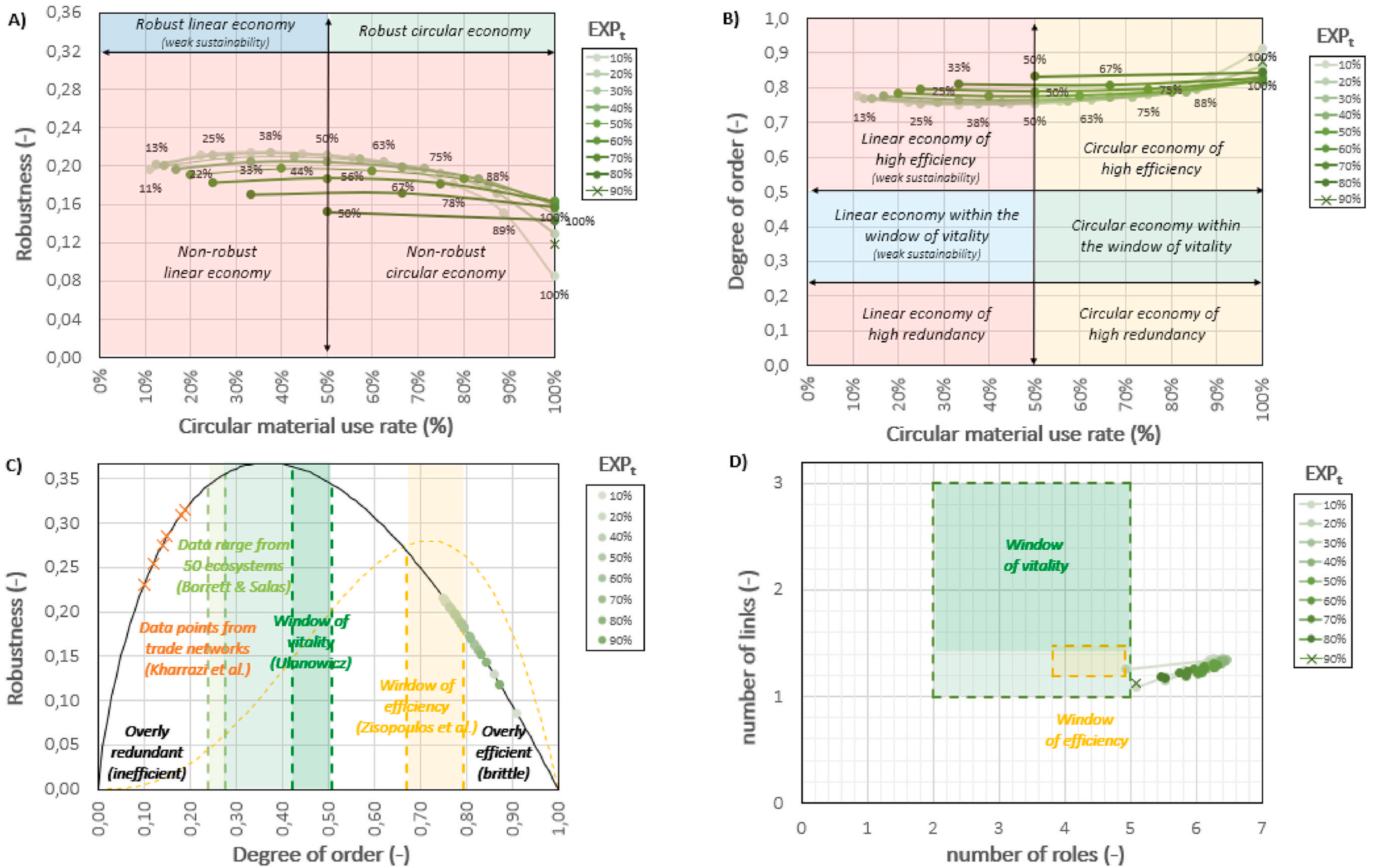

Fig. 6. The results of different 45 scenarios assessed in this research correspond to points colored in different shades of green. The shaded areas represent states which are: desirable (green), undesirable (red), potentially desirable (orange), and potentially desirable but unlikely (blue). The values over the data points correspond to the values of circular material use rate or circularity rate calculated from the parametric analysis. For an overview of the results in the form of a table the reader is referred to the Appendix C. A) Robustness versus circularity rate where the threshold for the *"window of vitality"* has been set (arbitrarily) at a robustness of 0,32, B) degree of order versus circularity rate, C) Robustness curve with: i) data from Ulanowicz et al. (2009) showing the range (dark green) of the *"window of vitality"* as calculated with the upper and lower values of the number of roles and of the number of links of natural ecosystems which have been proposed as *"ecological boundaries"* (with the exception that c_{min} was assumed to have a value of 1,4 instead of 1,0 since the latter would lead to a degree of order of ~1.0), ii) data from Borrett and Salas (2010) showing the range (light green) obtained by studying 50 ecosystems, iii) the whole area covered by the three shades of green showing the broader range of the window of vitality which is typically cited in literature, iv) data points (dark orange crosses) from Kharrazi et al. (2013) showing the results obtained from different types of trade networks (commodity, iron and steel, virtual water, oil and foreign direct investment), and v) data from Zisopoulos et al. (2022) showing the range (orange) obtained by studying the material and energy flow networks of the EU27 between 2010 and 2018 using data from Eurostat. This range was termed as the *"window of efficiency"* and it was obtained after refitting data to construct a new robustness curve which could in theory describe the evolution of these human-made systems by assuming that *"it is likely that other types of sustainable systems might cluster elsewhere along the interval $0 < \alpha < 1$"* (Ulanowicz, 2020), D) *"window of vitality"* (shaded in green) identified by plotting the *"ecological boundaries"* (Ulanowicz et al., 2009) and *"window of vitality"* (shaded in orange) identified by plotting the *"technological boundaries"* (Zisopoulos et al., 2022). The dark and light green areas show the effect on the size of the *"window of vitality"* by assuming a c_{min} of 1,4 or of 1,0, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

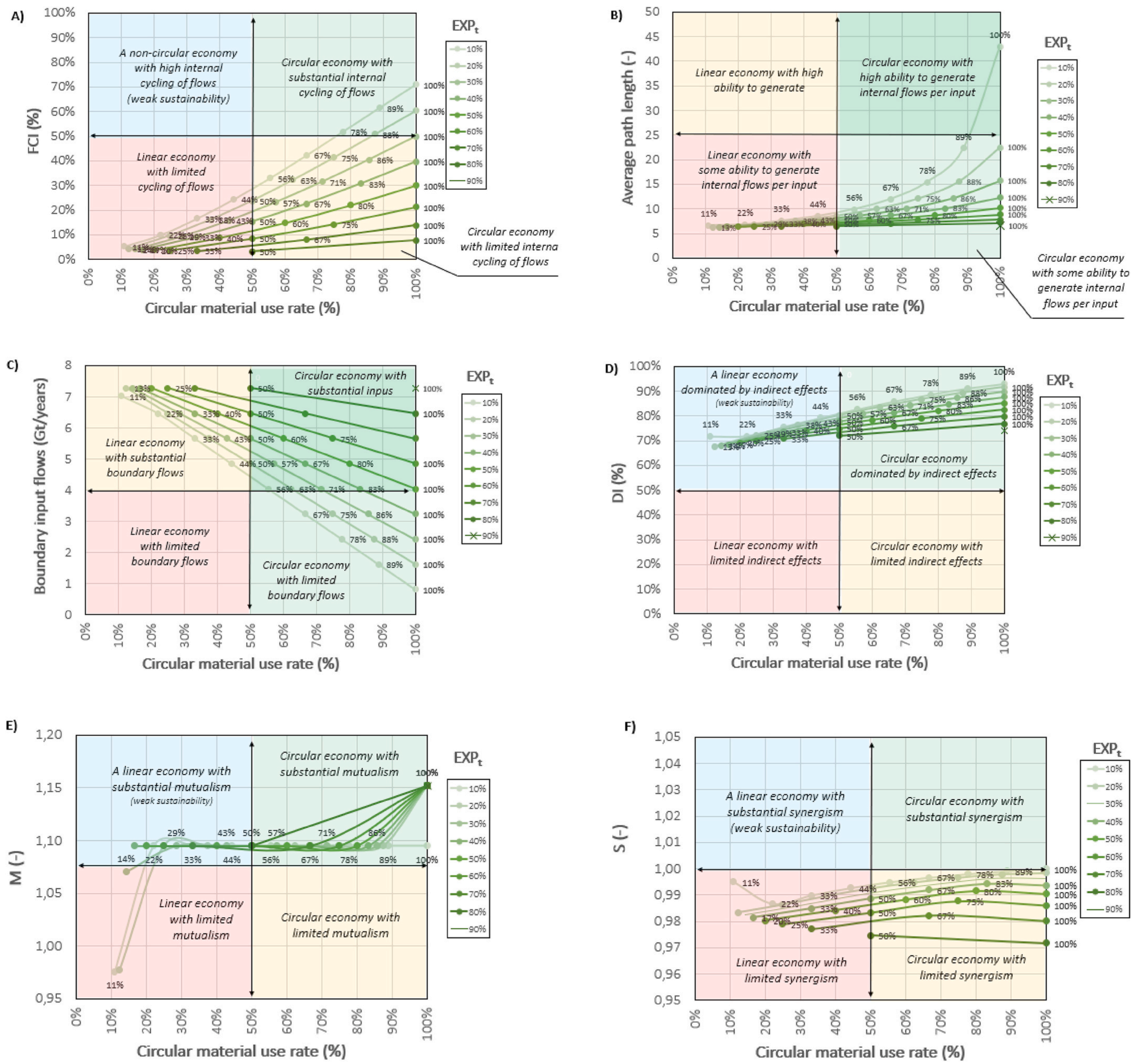

Fig. 7. The results of different 45 scenarios assessed in this research correspond to points colored in different shades of green. The values over the data points correspond to the values of circular material use rate or circularity rate calculated from the parametric analysis. For an overview of the results in the form of a table the reader is referred to the Appendix C. A) Finn's Cycling Index versus circularity rate, B) Average path length versus circularity rate. The midpoint which splits the graph in four quadrants has been chosen arbitrarily since "there is no generic optimum value or minimum value available, but that their magnitudes are system specific" (Fath et al., 2019a,b), C) boundary inputs versus circularity rate, D) Degree of indirect effects (*DI*) versus circularity rate, E) degree of mutualism (*M*) versus circularity rate, F) degree of synergism (*S*) versus circularity rate. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

$$APL = \frac{TST_{flow}}{\sum_{i=1}^{n} z_i} \tag{27}$$

4. Results and discussion

4.1. Parametric analysis of CMR

All combinations of material recovery rate and of export rate values which maximize the circularity rate imply a situation where the domestic material consumption of the EU27 becomes zero (Fig. 5). This suggests that within a fully circular EU27 there should be total reuse and recycling of material resources in combination with physical (material) exports but with no domestic consumption, no incineration, no presence or accumulation of toxic waste, self-sufficiency on critical raw materials, no rebound effects (Jevons paradox), and no material wearing or quality loss.

4.2. Setting a more realistic target for CMR

To examine the implications of setting a lower and more attainable circularity rate target, we reformulate the question by asking: under the same assumptions, what are the combinations of material recovery and exports rates which could, in theory, increase the circularity rate from approximately 11%[3] to 67%? Even though the value of 67% has been chosen arbitrarily it serves the purpose of highlighting (at least) three future possible states as combinations of recycling and export rates which can be visually identified on Fig. 5 due to the assumptions described under Methods.

The first transition direction (blue arrow) would require both material recovery and export rates to become 40%, and the domestic extraction of natural resources and domestic material consumption to be reduced to 4.04 Gt, and 1.62 Gt, respectively. The second one (red arrow) would require a material recovery rate of 20% and an export rate of 70% along with an increase in domestic extraction to 5.66 Gt and a decrease in domestic material consumption to 0.81 Gt. The third one (yellow arrow) would require a material recovery rate of 60% and an export rate of 10% followed by a substantial decrease both in the domestic extraction and domestic material consumption to 2.43 Gt. Following a similar reasoning, (at least) four different combinations of material recovery and export rates can be identified to reach an even lower circularity rate target of 50% (purple arrows).

4.3. Results of ascendency analysis

Given the stated assumptions, there were no scenarios which would theoretically lead to a robust circular economy within the *"window of vitality"* including those which maximized the circularity rate (Fig. 6). Additionally, no scenarios could lead to a linear yet robust economy (weak sustainability point of view) or to an economy which would be more resilient due to redundancy in its connections as it was shown to be the case of economic trade networks (Kharrazi et al., 2013). The highest robustness value obtained was 0,2149 in scenario 18 (30% RCV_R and 10% EXP_t) corresponding to a *CMR* of 33%. This scenario had also one of the highest values in the number of links at 1,35, as well as in the number of roles at 6,27. The lowest robustness value was 0,085 in scenario 45 (90% RCV_R and 10% EXP_t) which is one of the scenarios which maximize *CMR*. Interestingly, scenarios of low *CMR* (i.e., <50%) and particularly those of low export rates, could lead to higher robustness values than scenarios of high *CMR* (i.e., >50%). All scenarios of high RCV_R and of high EXP_t, particularly those which maximize *CMR*, could lead to a circular economy with a high degree of order (Fig. 6B), and therefore to low robustness which implies increased brittleness towards shocks. A few scenarios could lead to an economy within the *"window of efficiency"* (Fig. 6C) albeit only seemingly since all scenarios besides scenario 1 showed a higher number of roles than what has been proposed as a boundary for EU's material and energy flow networks (Fig. 6D). Scenario 1 which describes the situation in 2019, is the only one which fits almost within the *"window of efficiency"*. The other scenarios fall outside probably due to the assumptions made (e.g., reduced values in imports and higher material recovery rates and/or export rates).

4.4. Results of ecological network analysis and of other indicators

Fig. 7 shows the results from ecological network analysis and from the indicators *FCI* and *APL*. All these figures are discussed together to facilitate interpretation.

Intuitively, a high *FCI* value is desirable since it indicates a high internal cycling of the resource flow of interest. However, high internal cycling might also be the result of a stressful factor and there is no reference benchmarking *FCI* value which describes healthy ecosystems as it is context dependent (Fath et al., 2019a,b). Interestingly, the results show that a maximum circularity rate does not correspond to a maximum *FCI* (Fig. 7A). The maximum achievable *FCI* under the stated assumptions is 71% for scenario 45 (90% RCV_R and 10% EXP_t). For most of the rest of the scenarios the *FCI* index was <50% indicating future economies which could be either circular (*CMR* >50%) or linear (*CMR* <50%) yet with limited internal cycling of flows. A low *FCI* in a situation of high throughflow implies dependency on large boundary input flows (Fath et al., 2019a,b). This is the case for scenario 9 (10% RCV_R and 90% EXP_t) which had the lowest *FCI* of 3%, one of the highest throughput flows (47,7 Gt/year), accompanied with one of the largest values of boundary input flows (7,28 Gt/year).

Regarding *APL*, an increasing value corresponds to a system that is developed, and which can generate more flow activity per given boundary input flow (Fath et al., 2019a,b). The lowest *APL* (Fig. 7B) was 6,29 for scenario 2 (10% RCV_R and 20% EXP_t) which had very large boundary input flows (7,28 Gt/year) but also a relatively large throughput (45,8 Gt/year). The largest *APL* value achieved was of scenario 45 (90% RCV_R and 10% EXP_t) indicating that the network could generate 43,0 units of total flow activity per the (smallest assessed) boundary input flow (0,81 Gt/year) and smallest throughput (34,7 Gt/year). In this scenario indirect effects would account for 93% of the total flow activity implying a situation known as *"network non-locality"* (Fig. 7D). Indirect effects are thought to be beneficial in natural ecosystems (Fath, 2012) yet in this scenario they describe a highly brittle network. The lowest value for indirect effects was 67.6% obtained in scenario 2 (10% RCV_R and 20% EXP_t). Most of the scenarios assessed, both linear and circular, and particularly those of low export rates and of high recycling rates were dominated by indirect effects (Fig. 7D). All scenarios assessed (besides scenario 1 which depicts the situation of 2019, and scenario 2) had an $M > 1$ indicating that mutualistic relationships could prevail (Fig. 7E). When it comes to the degree of synergism, all scenarios assessed besides scenario 45 (90% RCV_R and 10% EXP_t), had $S < 1$ indicating network structures which could be more costly than beneficial in terms of flow activity (Fig. 7F).

Most of the scenarios assessed showed nodal relationships with a stable pattern as shown in Fig. 8. The exception were scenarios which maximized the circularity rate: 9, 17, 24, 30, 35, 39, 42, 44, and 45 where the relationships related to *"incineration"* and *"total emissions"* did not appear. The reason is that in these scenarios all output material flows were assumed to be fully recovered or fully exported individually (or in combination at different rates). Scenario 45 lacked the row and

[3] This *CMR* value was achieved in 2019 with a *DE* of 5.3 Gt, a *DMC* of 6.3 Gt, a RCV_R of 9.5%, and an EXP_t of 9.2%.

exploitative	+-	EE
exploited	-+	ED
mutualist	++	M
competitive	--	C

Left:

	Imports of waste for recycling	Imports excluding waste	Imports	Natural resources extracted	Direct material inputs	Processed material	Material use rate	Material accumulation	Waste treatment	Recycling	Backfilling	Exports	Exports of waste for recycling	Exports excluding waste	Dissipative flows	Incineration	Total emissions	Emissions to air	Waste landfilled
Imports of waste for recycling																			
Imports excluding waste		M	ED	ED	C	EE	M		ED	C		M							
Imports		EE	M	M	ED	C	EE		M	ED		EE							
Natural resources extracted		EE	M	M	ED	C	EE		M	ED		EE							
Direct material inputs		C	EE	EE	M	ED	C		EE	M		C							
Processed material		ED	C	C	EE	M	ED		C	EE		ED							
Material use rate		M	ED	ED	C	EE	M		ED	C		M							
Material accumulation																			
Waste treatment		EE	M	M	ED	C	EE		M	ED		EE							
Recycling		C	EE	EE	M	ED	C		EE	M		C							
Backfilling																			
Exports		M	ED	ED	C	EE	M		ED	C		M							
Exports of waste for recycling																			
Exports excluding waste																			
Dissipative flows																			
Incineration																			
Total emissions																			
Emissions to air																			
Waste landfilled																			

Right:

	Imports of waste for recycling	Imports excluding waste	Imports	Natural resources extracted	Direct material inputs	Processed material	Material use rate	Material accumulation	Waste treatment	Recycling	Backfilling	Exports	Exports of waste for recycling	Exports excluding waste	Dissipative flows	Incineration	Total emissions	Emissions to air	Waste landfilled
Imports of waste for recycling																			
Imports excluding waste		M	ED	ED	C	EE	M		ED	C		M				C	M		
Imports		EE	M	M	ED	C	EE		M	ED		EE				ED	EE		
Natural resources extracted		EE	M	M	ED	C	EE		M	ED		EE				ED	EE		
Direct material inputs		C	EE	EE	M	ED	C		EE	M		C				M	C		
Processed material		ED	C	C	EE	M	ED		C	EE		ED				EE	ED		
Material use rate		M	ED	ED	C	EE	M		ED	C		M				C	M		
Material accumulation																			
Waste treatment		EE	M	M	ED	C	EE		M	ED		EE				ED	EE		
Recycling		C	EE	EE	M	ED	C		EE	M		C				M	C		
Backfilling																			
Exports		M	ED	ED	C	EE	M		ED	C		M				C	M		
Exports of waste for recycling																			
Exports excluding waste																			
Dissipative flows																			
Incineration		C	EE	EE	M	ED	C		EE	M		C				M	C		
Total emissions		M	ED	ED	C	EE	M		ED	C		M				C	M		
Emissions to air																			
Waste landfilled																			

Fig. 8. Matrixes showing the flow relationships between the different nodes of the material flow network of EU27 representing different metabolic processes. *Left:* Pattern of scenarios which maximized the circularity rate: 9, 17, 24, 30, 35, 39, 42, and 44. *Right:* Pattern of the rest of the scenarios which did not maximize the circularity rate.

column which relates to the node *"natural resources extracted"* since it assumes that 90% of flows is recycled and 10% is imported.

Two outcomes from this analysis which are relevant for the rest of the scenarios which did not maximize the circularity rate, were the patterns of the nodes: *"incineration"* and *"recycling"*. The node *"incineration"* showed a competing relationship with *"imports excluding waste"*, with *"material use rate"*, with *"exports"*, and with *"total emissions"*, it showed an exploitative relationship of *"imports"*, of *"natural resources extracted"*, and of *"waste treatment"*, it showed a mutualistic relationship with *"direct material inputs"*, with *"recycling"*, and with itself, and it was only exploited by *"processed material"*. Scenario 2 was the only one which showed a slightly different pattern, having competing relationships between the node of *"incineration"* with *"imports"*, with *"imports excluding waste for recycling"*, with *"natural resources extracted"*, with *"material use rate"*, with *"waste treatment"*, with *"exports"*, and with *"total emissions"*. The node *"recycling"* showed an identical pattern with the one described for the node *"incineration"*. The rest of the relationships can be described by following a similar approach.

4.5. Answering the research questions

4.5.1. Implications of using the CMR indicator as a steering tool to transition to a CE

The results of the parametric analysis showed that even in a relatively independent and non-growing economy (in terms of material flows), 100% circularity as measured by circular material use rate indicator of Eurostat, seems unrealistic. This is an important aspect to consider especially for some Member States like the Netherlands which achieved the highest circularity rate (30.9%) among all European countries already in 2020 (European Commission, 2021), and which has the ambition to become fully circular by 2050 (Ministry of Infrastructure and the Environment, 2016).

Even though the transition directions discussed can mathematically lead to the same *CMR* target, some of those are arguably unlikely to occur. This becomes evident in the case of material exports. The export rate of the EU27 when expressed as a share of its gross domestic product, indeed showed a considerable increase within a decade [from 40% in 2010 to nearly 50% in 2019 (Eurostat, 2020)]. However, an export rate of 70% when expressed as a share of material flows for such a large (and, in an optimistic scenario, material-wise non-growing) economy seems unlikely.

High-level decisions related to the export and circular use of material resources would demand the implementation of different strategies and policies potentially across all governance levels within the EU27, as well as the restructuring of the European economy in terms of domestic extraction and domestic material consumption. It becomes then clear that the decision about which transition direction to follow at the EU level by using the circularity rate as a steering tool, is neither trivial for society and the environment nor straightforward since it could affect every sector and every citizen in varied ways and degrees both directly and indirectly. A successful transition will require substantial changes to take place both in international trade agreements as well as in the current extraction, production, and consumption patterns. Additionally, besides influencing funding schemes for the allocation of resources intended for climate change adaptation and mitigation actions, circularity aspects will also have to be addressed at multiple levels, simultaneously (European Commission, 2015; European Environment Agency, 2018).

Undeniably, recycling but also other waste reprocessing and management activities which aim to re-introduce material flows into the economy, are invaluable. However, they are not sufficient for solving waste-related problems and they cannot capture holistically the state of or progress towards a CE (Akenji et al., 2016).

It has been suggested that even a modest structural development in economic complexity could lead to evident non-uniform distribution of wealth in terms of its physical basis [i.e., *"measurable as work, fuel consumed or movement effected by fuel, food, and work"* (Bejan and R Errera, 2017)]. If this is the case, it is not unreasonable then to expect that a transition to a CE could lead to the manifestation of trade-offs, benefiting some parts of the society or the environment or the economy while disadvantaging others. This point was highlighted in a systematic literature review on international trade where the authors argued that knowledge gaps in trade flow dynamics could lead to the development of ineffective policies benefiting some countries in integrating circular practices while disadvantaging others (Barrie and Schröder, 2021), and even lead to a *"circularity divide"* (Barrie et al., 2022).

Considering the above, it is important that a balanced transition should not address circularity aspects only for the sake of maximizing the circulation of resources but mainly for promoting the development of a regenerative economy which drives inclusive prosperity.

4.5.2. Towards a regenerative circular economy

The added value of methods and indicators from RE is twofold. Firstly, they can be used as diagnostic tools to examine socio-economic systems in the form of interlinked networks. Theoretically, this could be done for a plurality of circulating resource flows. In this way, important network properties would be quantified to monitor their *"health"* (i.e., sustainability) by using several indicators such as their resilience, robustness, and degree of synergy between nodes. Secondly, they can be used to define clear criteria for resource cycling from an ecological perspective (Mayer et al., 2019) which is an essential aspect for socio-economic systems striving to become circular and operate within planetary boundaries (Raworth, 2017).

The results of ascendency analysis showed that none of the scenarios assessed could lead to a robust circular economy neither within the *"window of vitality"* nor within the *"window of efficiency"*, including the conditions which would theoretically maximize the circularity rate or *FCI*. Interestingly, scenarios of low *CMR* (i.e., $<$50%) and particularly those of relatively low export rates and recycling rates, could lead to higher robustness values than scenarios of high *CMR* (i.e., $>$50%) with the maximum robustness obtained at a RCV_R 30% and an EXP_t of 10% corresponding to a *CMR* of 33%. On the contrary, scenarios of high export rates could lead to brittle networks, even with relatively high material recovery rates. The results of ecological network analysis showed that despite the relatively high degree of mutualism, nearly all scenarios had a relatively low synergy between the network compartments, they showed relatively low *FCI* and *APL* values for most cases, and they were dominated by indirect flow effects (68%–93%) particularly in scenarios describing highly brittle networks.

Considering the above, and given the assumptions and constraints, we theorize that when economies are abstracted and analyzed as a metabolism (i.e., as a linear sequence of processes as shown in Fig. 3) with a low number of feedback loops then:

a) they do not reach maximum robustness as described by the *"window of vitality"* nor they necessarily fit into the *"window of efficiency"*.

b) their highest possible robustness seems to be achieved at a relatively low circularity rate (e.g., ~30–50%) as the result of a relatively low export rate (e.g., ~10% which is a similar export rate to that of 2019) and of a relatively low material recovery rate (e.g., ~30%). This combination of values for these two variables, even though they do not provide the largest degree of mutualism, of synergy, or of indirect effects, and do not lead to the best possible internal cycling of resources in this specific network configuration, they do allow for the largest number of roles and number of links to emerge, and they seem to lead to the highest capacity of the network to develop with the maximum value of 158,2 Gt bits/year obtained for scenario 3 (10% RCV_R and 30% EXP_t) with a *CMR* of 14%. Perhaps this finding could also be linked to and explained by the constructal law proposed by Adrian Bejan in 1996 which states that *"for a finite-size system to persist in time (to live) its configuration must change such that it provides easier access to its currents"* (Bejan and Lorente, 2010).
c) their nodal relationships seem be stable in one of two different patterns: either one that is *"poor"* in terms of relationships when the system is fully circular (*CMR* = 100%) or one that is *"richer"* when it is not (*CMR* <100%).

4.5.3. Which window to choose?

The framing of the *"window of vitality"* within *"ecological boundaries"* has been identified by using two important indicators: the number of roles and the number of links (or link density) of an ecosystem. The former describes *"a group of nodes that takes its inputs from one source and passes them to a single destination. The source and destination can be a group of nodes as well"* (Zorach and Ulanowicz, 2003). The latter measures *"the effective connectivity of the system in terms of links per node which is directly related to resilience"* (Lietaer et al., 2010).

Our research suggests that the choices made for modelling the system of interest as a linear metabolism or as a sectorial interconnected network play an important role on the outcome of ascendency analysis and ecological network analysis. Another important example of such a choice is whether links between the nodes of the network are considered as edges (which simply connect nodes) or as additional nodes implying that they have some functional *"actor's role"* in the network (Panyam and Layton, 2019b).

We stress that any attempt to develop policies for driving socio-economic networks towards either window (either that of vitality or that of efficiency) should be assessed very carefully for at least two reasons. Firstly, because striving towards maximizing robustness within the *"window of efficiency"* seems intuitively wrong given that the world economy is dominated by linear unsustainable production and consumption patterns (Circle Economy, 2022) which harm rather than regenerate nature (United Nations Environment Programme, 2021; United Nations Environment Programme (UNEP), 2021 and United Nations Environment Programme, 2021; Intergovernmental Panel on Climate Change (IPCC), 2022). Secondly, redesigning human-made networks to fit within the *"window of vitality"* could theoretically maximize robustness for one type of resource flow but it would not guarantee that the developed network would be robust for other circulating resources or that it would lead to a future society that is desirable from other perspectives (Zisopoulos et al., 2022). Undeniably, more case studies are needed to establish a better understanding of the inherent complexities of socio-economic networks when analyzed with methods such as ecological network analysis and ascendency analysis (Ulanowicz et al., 2009).

Ultimately, a regenerative socio-economic system is one which focuses on the well-being of people and all life on Earth as well as on the ability of nature for self-renewal. Value in such a system is to be captured in an integrated, non-monetary way which recognizes and accounts for all natural stocks and flows of the natural capital as well as of all ecosystem services, and where financial risk and return are considered as constraints rather than optimization goals with equity (instead of debt) being the driver for economic development (CirclNL, 2021).

4.6. Limitations

Even though our analysis was not a life cycle assessment study, it did fit three of the four criteria for predictive validity assessment presented by Huppes and Schaubroeck (2022) since the assessed scenarios intend: 1) to explore the effect of export rates and material recovery rates which could influence the circularity of the European economy, 2) to investigate non-linearities which implicitly capture decisions at the meso-level (national) summarized at the macro-level (EU), and 3) which implicitly capture broader socio-economic developments. However, the scenarios assessed were not linked to other dynamics which could potentially be affected by the material recovery rate and export rate, and they did not directly link to possible decision procedures given that each Member State develops their own national strategies towards a circular economy. An important limitation is that the mathematical model describes a macro-level analysis of the EU27 material flows, and as such it is nearly impossible to compare and validate the output values to independent field or experimental data sets. Therefore, by considering that the simulated scenarios extend outside the realm of observed conditions, we think that besides the repetition of the modelling analysis by other scientists to verify or falsify these theoretical findings, operational validation might not even be possible. Another limitation is that we assumed the *"dissipative flows"* and the *"total emissions"* to be affected in a proportional way to the domestic material consumption (Appendix B). Here, we also stress that our research does not intend to predict the future, which is volatile and subject to dynamic political, environmental, social, technological, economic, and legal factors. Rather, it should be seen as a useful exercise for identifying and being mindful of potential system relations (Huppes and Schaubroeck, 2022).

Another important limitation is that the cutoff points of the indicators studied were set arbitrarily as thresholds for classifying scenarios according to the developed framework (Fig. 2). This is due to the lack of benchmark values highlighting the need for more studies on socio-economic systems.

Furthermore, shocks were perceived only in a broad, abstract, and hypothetical context. They have been considered as any internal or external factor which could substantially affect the function of at least one of the nodes which represent different functions of the EU's material flow metabolism. Future studies should aim at exploring how to identify, model, and account for different types of shocks within ascendency analysis and ecological network analysis of complex socio-economic systems.

5. Conclusions

The quantification of regenerative and resilience aspects of complex socio-economic systems which strive to maximize their circulation of resources, is a research topic which is largely unexplored. To this end, we develop a conceptual framework to provide a comprehensive perspective on circularity and regeneration which can be useful to policy makers and researchers. By using this framework, we examine whether there are theoretical limits to robustness as the result of a linear socio-metabolic structure, and how those limits could theoretically be affected by transitioning to a circular economy. We apply ascendency analysis and ecological network analysis on the material flow metabolism of the EU27 by using data from Eurostat. More specifically, we conduct a parametric analysis on the circularity rate (or circular material use rate) indicator by varying the values of two key variables: the material recycling rate and the export rate.

Among other findings, the results showed that none of the scenarios studied achieved maximum robustness, including those which would theoretically maximize the circularity rate or Finn's Cycling Index. The linear metabolic structure of the EU27 (as described by Eurostat) seems to achieve its highest robustness values at low circularity rates (i.e., ~20–50%) and particularly at low export rates (i.e., <40%), with the maximum robustness of 0,2149 obtained at a material recovery rate (RCV_R) of 30% and an export rate (EXP_t) of 10% corresponding to a circularity rate (CMR) of 33%. This is possibly due to the large number of roles and number of links per node emerging in such a network structure under the given assumptions which also seems to lead to a higher capacity to develop when compared with other scenarios. On the contrary, scenarios of higher export rates but also of higher material recovery rates seem to lead to brittle networks with a lower number or roles and number of links.

Furthermore, the parametric analysis suggests that a circularity rate of 100% in the EU27 is unrealistic even in an optimistic situation of extensive efforts towards a CE. A target that is lower than 100% seems to be more attainable, but even so, it would require substantial restructuring in the European economy.

This theoretical study illustrates how principles and indicators from regenerative economics can be of service for developing transition strategies towards a regenerative circular economy.

Author contributions

F.K.Z. conceived of the idea of the research, compiled the document structure, conducted the data collection and the quantitative analysis, and wrote the text as the main author. D.A.T., D.F.J.S., M.d.J., X.T., and R.E.U. provided constructive criticism and suggestions to improve the manuscript and reviewed the text. All authors contributed significantly to this work by reading, knowledge-sharing, and editing. All authors have read and agreed to the published version of the manuscript. The authors are grateful to the reviewers and editors for their constructive feedback which helped illuminate the novelty of this work.

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Competing interests

The authors declare no competing interests.

Data availability

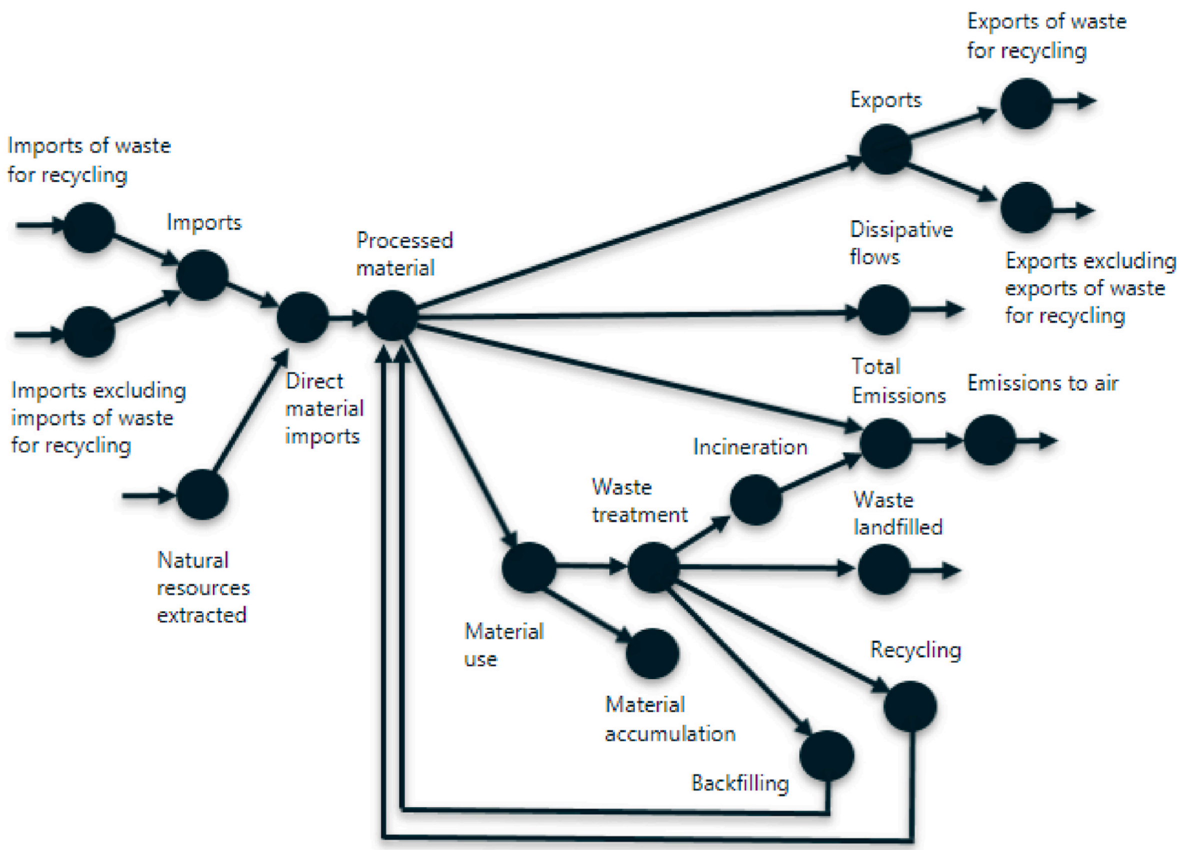
The dataset analyzed in this study was obtained by the reported values from Eurostat on the material flow diagram of the EU27 for 2019 (in Gt) accessed on the September 28, 2021 (Eurostat, 2021b).

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.

Appendix A

Network abstraction of Fig. 3 which is used for the scenario analysis.



Appendix B

Below is the approach followed for constructing the material flow networks of all scenarios based by using Eurostat data of the EU27 for 2019 (Fig. 3). The data were accessed on the September 28, 2021 (Eurostat, 2021b). The value for the Processed Material considered for scenario 1 was the calculated value (i.e., 8,01 Gt/year) and not the one illustrated in Fig. 3 (i.e., 8,08 Gt/year). For the rest of the scenarios the total Processed Material was considered at 8,08 Gt/year. The values of some flows have been calculated as percentages of the domestic material consumption proportionally to scenario 1 (assumption).

$$DE = PM - IMP_t - RCV_R - Backfilling$$

where $PM = 8,08\ Gt/year$, $IMP_t = 10\%\ PM = 0,808\ Gt/year$, $Backfilling = 0$,

$$\frac{RCV_R}{PM} = \%\ based\ on\ scenario$$

$$DMI = DE + IMP_t$$

$$IMP_t = IMP_w + IMP_{excl.\ waste}$$

where $IMP_w = 0$

$$DMC = DMI - EXP_t$$

$$EXP_t = EXP_w + EXP_{excl.waste}$$

where $EXP_w = 0$, $\frac{EXP_t}{PM} = \%\ based\ on\ scenario$

$$Waste\ treatment = RCV_R + Incineration + Waste\ landfilled$$

where $Incineration = 1.7\%\ DMC$, $Waste\ landfilled = 11\%\ DMC$

$$Total\ emissions = 37\%\ DMC$$

$$Dissipative\ flows = 4\%\ DMC$$

Appendix C

Results of ascendency analysis and ecological network analysis for all 45 scenarios examined. The first scenario (upper left quadrant with an export rate EXP_t of 9,2% and a material recovery rate RCV_R of 9,5%) represents the situation of 2019 as described in Fig. 3. For the rest of the scenarios their values were increased incrementally by a constant value of 10%. Σz_i is the total boundary input flows (Gt/year), $T_{..}$ is the total system throughput (Gt/year), *FCI* is Finn's cycling index (%), α is the degree of order (−), *M* is the degree of mutualism (−), *DI* is the degree of indirect effects (−), *R* is the robustness (−), *S* is the degree of synergism (−), *n* is the number of roles (−), *c* is the number of links (−), *APL* is the average path length (−), *C* is the capacity to develop (Gt bits/year), *A* is the ascendency (Gt bits/year), and Φ is the redundancy or overhead (Gt bits/year). Depending on the indicator, the color scales represent desired values (or not).

Σzi	α	R	n	C
T..	M	S	c	A
FCI	DI%	DI	APL	Φ

RCV_R \ EXP_t	9,2%					20%					30%					40%					50%					60%					70%					80%					90%					100%				
9,5%	7,0	0,777	0,196	4,94	138	7,28	0,769	0,202	6,2	157	7,28	0,77	0,20	6,26	158	7,28	0,776	0,197	6,22	157	7,28	0,784	0,191	6,12	155	7,28	0,795	0,182	5,96	152	7,28	0,811	0,170	5,75	147	7,28	0,833	0,152	5,47	139	7,28	0,874	0,118	5,08	128					
	46,6	0,976	0,995	1,26	107	45,7	0,978	0,983	1,3	120	46,0	1,071	0,982	1,31	122	46,3	1,095	0,982	1,30	122	46,5	1,095	0,980	1,28	122	46,8	1,095	0,979	1,26	121	47,1	1,095	0,977	1,23	119	47,4	1,095	0,975	1,19	116	47,7	1,152	0,958	1,12	112					
	5%	72%	2,50	6,63	31	4%	68%	2,03	6,28	36	4%	68%	2,00	6,32	36	4%	69%	2,02	6,36	35	4%	69%	2,06	6,40	34	4%	70%	2,13	6,44	31	4%	71%	2,23	6,48	28	3%	72%	2,37	6,52	23	3%	74%	2,62	6,56	16					
20%	6,47	0,756	0,211	6,21	153	6,47	0,76	0,211	6,35	156	6,47	0,760	0,209	6,39	157	6,5	0,766	0,204	6,36	157	6,47	0,775	0,197	6,27	154	6,47	0,789	0,187	6,10	151	6,47	0,808	0,172	5,87	145	6,47	0,843	0,144	5,54	135										
	44,1	1,095	0,987	1,34	116	44,4	1,095	0,986	1,35	118	44,6	1,095	0,986	1,34	120	44,9	1,095	0,985	1,33	120	45,2	1,095	0,984	1,30	120	45,5	1,095	0,983	1,27	119	45,8	1,095	0,982	1,23	117	46,1	1,152	0,972	1,17	114										
	10%	72%	2,62	6,81	37	10%	72%	2,53	6,9	38	9%	73%	2,55	6,9	38	9%	74%	2,60	6,9	37	9%	74%	2,68	7,0	35	8%	75%	2,79	7,0	32	8%	76%	2,92	7,1	28	8%	77%	3,11	7,1	21										
30%	5,66	0,751	0,2147	6,26	151	5,66	0,753	0,2133	6,41	153	5,66	0,757	0,210	6,45	154	5,66	0,766	0,204	6,42	153	5,66	0,778	0,196	6,31	150	5,66	0,795	0,182	6,14	145	5,66	0,827	0,157	5,84	137															
	42,7	1,095	0,990	1,354	113	43,0	1,095	0,990	1,357	115	43,3	1,095	0,989	1,348	117	43,6	1,095	0,989	1,33	117	43,9	1,095	0,988	1,30	117	44,2	1,095	0,988	1,26	116	44,5	1,152	0,980	1,20	113															
	17%	76%	3,14	7,6	37	16%	76%	3,15	7,6	38	16%	77%	3,22	7,7	37	15%	78%	3,31	7,7	36	15%	78%	3,42	7,8	33	14%	79%	3,56	7,8	30	14%	80%	3,73	7,9	24															
40%	4,85	0,753	0,2135	6,25	145	4,85	0,756	0,212	6,40	148	4,85	0,762	0,207	6,44	148	4,85	0,773	0,199	6,39	146	4,85	0,790	0,186	6,27	143	4,85	0,820	0,163	6,02	135																				
	41,4	1,095	0,993	1,35	109	41,7	1,095	0,992	1,35	112	42,0	1,095	0,992	1,34	113	42,3	1,095	0,992	1,31	113	42,6	1,095	0,992	1,28	113	42,8	1,152	0,986	1,22	111																				
	24%	79%	3,82	8,5	36	24%	80%	3,94	8,6	36	23%	81%	4,07	8,7	35	23%	81%	4,20	8,7	33	22%	82%	4,35	8,8	30	21%	83%	4,53	8,8	24																				
50%	4,04	0,761	0,208	6,18	138	4,04	0,765	0,205	6,31	140	4,04	0,774	0,198	6,34	140	4,04	0,790	0,186	6,28	137	4,04	0,819	0,164	6,08	131																									
	40,1	1,095	0,995	1,33	105	40,4	1,095	0,995	1,33	107	40,6	1,095	0,995	1,31	108	40,9	1,095	0,994	1,28	108	41,2	1,152	0,990	1,22	107																									
	33%	83%	4,75	9,9	33	32%	84%	4,99	10,0	33	32%	84%	5,17	10,1	32	31%	85%	5,36	10,1	29	30%	85%	5,55	10,2	24																									
60%	3,23	0,775	0,198	6,03	130	3,23	0,782	0,193	6,15	131	3,23	0,796	0,182	6,16	130	3,23	0,824	0,160	6,02	124																														
	38,7	1,095	0,997	1,30	100	39,0	1,095	0,997	1,29	102	39,3	1,095	0,996	1,26	103	39,6	1,152	0,994	1,21	103																														
	42%	86%	6,01	12,0	29	41%	87%	6,38	12,1	29	41%	87%	6,63	12,2	26	40%	88%	6,87	12,2	22																														
70%	2,43	0,797	0,181	5,82	119	2,43	0,809	0,172	5,91	119	2,43	0,837	0,149	5,84	116																																				
	37,4	1,095	0,998	1,25	95	37,7	1,095	0,998	1,23	97	38,0	1,152	0,996	1,19	97																																				
	52%	89%	7,74	15,4	24	51%	89%	8,22	15,5	23	50%	90%	8,55	15,7	19																																				
80%	1,62	0,834	0,152	5,52	107	1,62	0,860	0,130	5,54	104																																									
	36,1	1,095	0,999	1,19	89	36,4	1,152	0,998	1,15	90																																									
	62%	91%	10,11	22,3	18	60%	92%	10,67	22,5	15																																									
90%	0,81	0,911	0,085	5,08	89																																														
	34,7	1,095	1,000	1,08	81																																														
	71%	93%	13,3	43,0	8																																														
100%																																																			

Appendix D. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clpl.2022.100014.

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