Ecological Economics 190 (2021) 107190

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Methodological and Ideological Options

Between you and I: A portfolio theory of the circular economy

Frank Figge[a,b,*], Andrea Stevenson Thorpe[c,d], Siarhei Manzhynski[b]

[a] ESCP Business School, 79, Av. de la République, 75011 Paris, France
[b] Umeå University, Umeå School of Business, Economics and Statistics, Biblioteksgränd 6, 901 87 Umeå, Sweden
[c] Kedge Business School, Domaine de Luminy – BP, 921 Rue Antoine Bourdelle, 13288 Marseille, Cedex 9, France
[d] Macquarie University, Macquarie Business School, Sydney, NSW, Australia

ARTICLE INFO

Keywords:
Circular economy
Eco-efficiency
Portfolio theory

ABSTRACT

By using resources more circularly, individual resources users hope to contribute to a more eco-efficient and sustainable resource use. Whether resources are used sustainably is decided at the macro-level, raising the question if, as well as how, the efficient and circular use of resources at the micro-level adds up to their efficient and circular use on the macro-level. Currently, the link between the circular use of resources at micro- and macro-levels is under-theorized. The symbiotic relationship between individual resource users enables a reduction in the resource use at the macro-level. In this conceptual paper, we argue that an analogous link exists in finance where desirable investment return is linked to undesirable investment risk, and that via the generation of efficient portfolios, individual risks are at least partially diversified away. As our main contribution, we theorize the circular economy, both in its perfect and imperfect forms, using modern portfolio theory. Our theory identifies the drivers of circular resource use and shows under which conditions individual resource use contributes to the circular use of resources.

1. Introduction

Together, a growing population and an escalating demand for a greater number of products ostensibly mean the use of more resources (Chertow, 2000b; Commoner, 1972; Ekins and Hughes, 2017). On the one hand, giving people access to products — especially those which improve standards of living and attend to issues of poverty — is clearly desirable. On the other hand, this implies the need for non-renewable resources, of which we only have a limited supply on ‘spaceship Earth’ (Boulding, 1966). Both in theory and practice, this tension has been partially addressed by strategies of eco-efficiency (DeSimone and Popoff, 1998; Eder et al., 2021; World Business Council for Sustainable Development, 2000), where the aim is to make ‘more with less’. In the long-term though, the problem remains: No matter how efficiently we use resources, they will eventually be depleted. As a result, research into the circular economy is rapidly gaining traction (Ghisellini et al., 2016; Kirchherr et al., 2017; Pearce and Turner, 1990), where principles of circularity are positioned as a more adequate means of addressing the issue, albeit in a range of formats (e.g. Bauwens et al., 2020). In practice, the circular economy is also increasingly popular, and in some realms has been established for decades. Geng et al. (2019) for example, describe twenty year old eco-industrial parks in China and South Korea and the informal systems of recycling in India and Brazil (see also, Dong et al., 2021a; Fuss et al., 2021; Sharma and Pandey, 2020; Zeng et al., 2021).

However, despite the volume of work into the circular economy, it is under-theorized, and as Korhonen et al. (2018, p. 37) argue, “superficial and unorganized” — and even in practice initiatives are often isolated from each other (Geng et al., 2019). Whilst important insights have been garnered into, for example, ways of measuring circularity (e.g. Elia et al., 2017; Figge et al., 2018; Geng et al., 2013; Parchomenko et al., 2019), such strands of research are relatively contained to their specific niches, and remain disconnected to other aspects of circularity. At a ‘higher level’, where we might consider the organization of circular economy systems as a whole, again we see nuanced conversations that reflect a multitude of disciplines. As Korhonen et al. (2018, p. 39) explain, ideas from different scientific and semi-scientific streams such as industrial ecology (Graedel, 1996), eco-efficiency (DeSimone and Popoff, 1998), or cleaner production (Stevenson and Evans, 2004) have generated interesting and valuable insights, which nevertheless leave a disjointed and fragmented conversation on the theory that underpins circular systems as a whole. The

* Corresponding author at: ESCP Business School, 79, Av. de la République, 75011 Paris, France.
E-mail addresses: figge@sustainablevalue.com (F. Figge), andrea.thorpe@kedgebs.com (A.S. Thorpe), siarhei.manzhynski@umu.se (S. Manzhynski).

https://doi.org/10.1016/j.ecolecon.2021.107190
Received 8 October 2020; Received in revised form 1 June 2021; Accepted 9 August 2021
Available online 18 August 2021

system of industrial symbiosis at Kalundborg, for instance, offers an exemplary illustration of how circularity might be organized (Ehrenfeld and Gertler, 1997). Yet it is confined to the specific geographical, economic, and organizational contexts in which it is embedded, making theorization — perhaps even within the specific framing of industrial symbiosis — rather difficult. As such we are left with a lack of comprehensive theory, especially that which concerns the organization of circular systems. It is to this problem that we respond to with this conceptual paper, i.e. our overarching main objective here is to contribute to the theorization of the circular economy.

From one perspective, the need to use resources circularly seems self-evident, and the concept of the circular economy is rather simple, negating the need for such theorization. However, two observations point to the converse. First, there is a discord between research and practice: In principle, fully circular systems are straightforward and are frequently mapped out in the literature with designs that stipulate the use and reuse of resources over and over again, accumulating no waste in the process, and no need for the use of virgin resources (Figge et al., 2017). However, in practice, resource use is very often neither fully circular nor fully linear. Copper is used 1.9 times before it is disposed of (Eckelman and Daigo, 2008), and nickel is used about three times (Eckelman et al., 2012), for example, indicating that some waste is a realistic output even in the most circular of systems. Second, recent research in this journal points to a new 'ontological reality' (Figge et al., 2021) that arises from collaborations between resource users who initiate a group-based system of circularity. Simply put, Figge et al. (2021) demonstrate that the degree of circularity must be assessed at the group level, but not by merely adding together individual resource users as, they intimate, 'the whole is greater than the sum of the parts'. This is reflective of the complexity of imperfectly circular systems, i.e. where some waste occurs, but also hints at a further complication: The amount of waste generated is irregular and differentiated across resources users and with respect to the specific resource in question. In short, micro-level resource use does not sum up neatly to macro-level resource use.

Thus, the circular economy as a concept is rather more complex than perhaps first thought, hinting at the need for greater theorization to understand, for example, its drivers and organization, or its implications for how society manages earth's natural resources. To build effective theory, however, we argue that parameters are necessary that distinguish, for example, imperfect systems from those which assume no waste. As such, this conceptual article contributes to the former, i.e. our main goal is to build theory on the organization of imperfect systems of circularity. To do so, we borrow from financial studies — and specifically modern portfolio theory (Markowitz, 1952, 1959) — as we argue that a similar phenomenon can be observed in financial markets: While the returns of individual assets add up to the return of a portfolio of assets, the risks do not. The risks of individual assets may disappear completely, partly, or not at all at the portfolio level. We transfer this insight from portfolio theory to the use of resources in imperfectly circular systems in general and we explore the implications of differing levels of analysis in particular. As such, our main contribution concerns the variables that influence greater eco-efficiency, as well as the implications for how society manages its use of natural resources. The overall research question on which we build our theory is: 'What insights can modern portfolio theory offer into how the circular economy can be organized in ways that optimize resource use?' By 'optimization' we mean the minimization of resource use or the maximization of eco-efficiency.

To build our theory, we organize the remainder of our article as follows. The following chapter provides a succinct introduction to portfolio theory, in which we highlight its seminal principles from Markowitz (1952, 1959), with which we start. From this in our third chapter we build a 'portfolio theory of circular resource use' — based on financial portfolio theory as introduced in the previous chapter. Chapter four develops our theoretical contribution where we discuss what we can learn from our proposed 'portfolio theory of circular resource use', before we conclude with some suggestions for further research and some final remarks.

2. Financial portfolio theory

Decisions in finance are dominated by two variables: Expected return and expected risk. Investors are typically assumed to be risk-averse, i.e. they prefer low risk over high risk. However, investors simultaneously prefer high returns over low returns. The problem is that high returns are associated with high risks. Simply put, if investors want the former, they need to accept the latter (Fama, 1970).

Whilst this interplay between return and risk, and how to balance the two, has been discussed as early as the 16th century (Shakespeare, 1750), portfolio theory (Markowitz, 1952, 1959) has addressed this problem in more modern times. At its crux, the theory proposes that grouping assets (or individual investments) into portfolios enables risk-averse investors to potentially maximize their returns for a given level of risk. To do this, portfolio theory works on a simple principle: Whilst the overall return on the portfolio of assets reflects the sum of its parts, i.e. its individual assets, the same is not true for risk, which is ameliorated through diversification — at least partially. Interestingly, modern portfolio theory has proved to be robust: Whilst a popular theory in finance with contemporary scholars continuing to seek fresh nuances, extensions and applications (e.g. Bajaj, 2021; Eaton et al., 2019; Ünlü and Xanthopoulos, 2021), its fundamental principles have remained relatively intact.

In short, portfolio theory reveals the contrast between the risk-return profile of each individual asset, and the risk-return profile of the portfolio as a whole, to which the individual assets belong. To illustrate, we can use the example of two individual assets — 'A' and 'B'. First, like any other, A and B each have a risk-return profile, as an individual asset. In other words, A, for instance, might have a potentially high return, but for a relatively high degree of risk. Risk is measured as the standard deviation or variance of expected returns, i.e. the variance of an individual asset describes the fluctuation of its expected return, and, as a general rule, the higher the degree of fluctuation, the greater the degree of risk. Second, to determine the risk-return profile of A and B as a portfolio, we additionally need to know the extent to which the returns of A and B co-vary. In other words, to what extent — if any — the return of one asset goes up (or down) when the other goes up (or down), as a correlation.

For a portfolio of two assets, such as our simple example above, the return of the portfolio is the weighted average of the return of the two assets (e.g. Brealey et al., 2020, p. 182).

Portfolio $return = x_a{}^* r_a + x_b{}^* r_b$

with:
x_a: Percentage invested in asset A
x_b: Percentage invested in asset B
r_a: return of asset A
r_b: return of asset B

The risk associated with the portfolio can be calculated using a covariance matrix (e.g. Brealey et al., 2020, p. 182), as Table 1 indicates. This risk, in terms of the variance of the portfolio, corresponds to the overall sum of the four values in the four boxes below. The top left (AA) and the lower right (BB) boxes each correspond to the square of the percentage invested in asset A or B respectively, multiplied by the variance of the asset. The lower left (BA) and the upper right (AB) boxes follow an identical rule, with an addition: BA and AB both depend on the percentage invested in asset A and B, as well as the covariance of A and B, i.e. the degree to which they fluctuate in the same or opposite direction. The covariance can also be expressed as the product of the standard deviations of A and B multiplied by the correlation coefficient of A and B.

The calculation of the portfolio risk, measured as the variance of

Table 1
Covariance matrix illustrating the portfolio risk of AB.

	A (x_a, σ_a)	B (x_b, σ_b)
A (x_a, σ_a)	$x_a * x_a * \sigma_a * \sigma_a = x_a^{2} * \sigma_a^{2}$	$x_a * x_b * \sigma_{ab} = x_a * x_b * \rho_{ab} * \sigma_a * \sigma_b$
B (x_b, σ_b)	$x_a * x_b * \sigma_{ab} = x_a * x_b * \rho_{ab} * \sigma_a * \sigma_b$	$x_b * x_b * \sigma_b * \sigma_b = x_b^{2} * \sigma_b^{2}$

returns, can therefore also be expressed as:

$$\text{Portfolio risk} = x_a^2 * \sigma_a^2 + x_b^2 * \sigma_b^2 + 2(x_a x_b \rho_{ab} \sigma_a \sigma_b)$$

with:

σ_a: standard deviation of asset A
σ_b: standard deviation of asset B
ρ_{ab}: Correlation of assets A and B

We should note that the square root of the variance corresponds to the standard deviation.

The most important aspects of portfolio theory are depicted in Fig. 1, where we can further explain the risk-return relationship using our simple example of a portfolio that comprises of assets A and B. As shown, asset A has an expected return of 10% and a standard deviation (risk) of 10%. B's return is 25% and the standard deviation is 20%.

Each of the three lines (1, 2, and 3) in Fig. 1 represents a different correlation between assets A and B. Different points on each line (e.g. Y and Z on line 2) reflect differing combinations of investments into assets A and B. When a point is close to one asset but further away from another, this reflects a more extensive investment in the former and less so in the latter. For example, point Y on line 2 indicates that the investment into asset A is much greater than that into asset B.

In Fig. 1, line 1 corresponds to a perfect positive correlation between A and B (correlation coefficient of +1), i.e. when the return of asset A increases, the return of asset B also increases. Line 2 represents a perfect negative correlation between A and B (correlation coefficient of −1), i.e. when the return of asset A increases the return of asset B decreases. Line 3 corresponds to circumstances where the returns are uncorrelated (correlation coefficient of 0).

When assets are perfectly positively correlated (line 1, Fig. 1), investing in both assets at the same time does not reduce risk. A higher return can only be achieved by accepting a higher risk. Line 2 shows a situation where assets are perfectly negatively correlated; it stretches from point A to point B passing through point X, reflecting that risk can be completely eliminated. This point where the portfolio risk has been completely eliminated is calculated using the formula for portfolio risk above. In our particular example, it corresponds to an investment of 67% in asset A and 33% in asset B. With this specific spread of investment across A and B, the return of the entire portfolio can be predicted with certainty. Whilst neither a perfectly positive nor a perfectly negative correlation are likely to exist in practice, it remains that the more positive — or negative — the correlation is, the more the relationship between risk and return of the portfolio will reflect line 1 or 2 respectively.

Line 3, reflecting a lack of correlation between the returns of A and B, is somewhere between lines 1 and 2, and is somewhat more intriguing, not least because it accommodates more realistic portfolios in practice. The portfolio on line 3 in Fig. 1 that has the lowest possible risk (point Y) consists of both assets rather than just asset A, which has a lower individual risk than asset B. But, as we have argued, for a risk-averse investor, it is irrational to exclusively invest in the asset with the lowest risk, if the aim is to reduce investment risk. The only exception is the case where all assets are perfectly positively correlated — which, again as we have argued, is a somewhat unrealistic circumstance in practice.

Thus, the relation of return per unit of risk can be interpreted as an investment efficiency (Fama and MacBeth, 1973). Line α in Fig. 1 represents different combinations of return and risk, and it is tangent with line 3 at point Z. This indicates the point which reflects the highest degree of efficiency. Additionally, both assets are needed, and it is different from the point of lowest risk, indicated by point Y.

The scenario of just two assets within a single portfolio enables us to showcase the most relevant insights of portfolio theory for this paper, in the simplest way. However, in practice, portfolios are likely to consist of many more assets, an example of which we illustrate in Fig. 2.

To the right of the curve in Fig. 2 are multiple dots that each represent an individual asset with a particular expected return and risk. The curve itself is the efficient frontier (Markowitz, 1952), i.e. the best possible combinations of return and risk of the portfolio overall. The efficient frontier is generated by specific combinations of the assets. Any combination of assets below the efficient frontier are inefficient, i.e. for any inefficient combination it is possible to either have a higher return with the same risk or lower risk for the same return. In Fig. 2, all of the

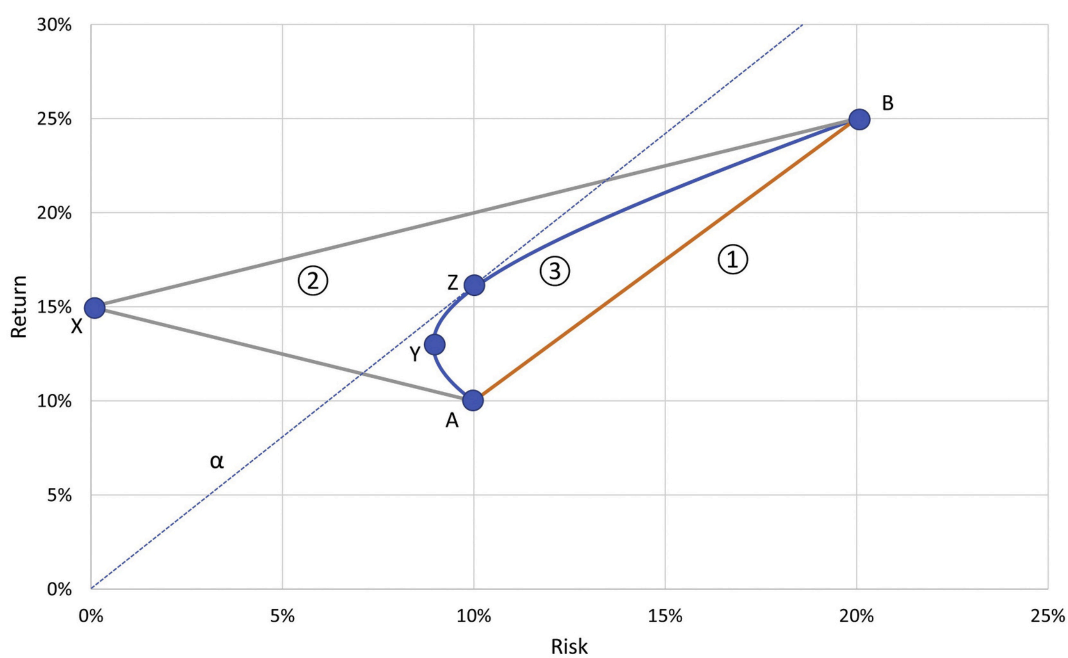

Fig. 1. Financial portfolio theory (two assets).

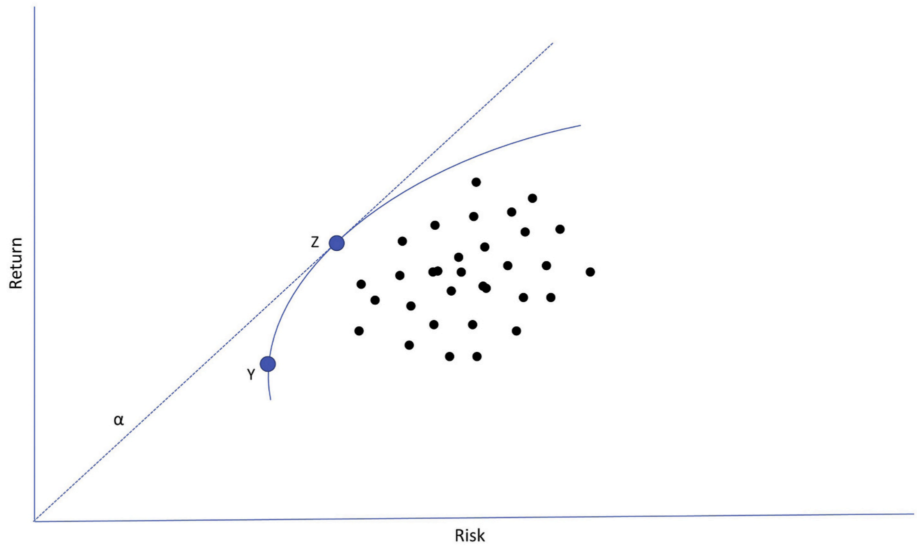

Fig. 2. Financial portfolio theory (multiple assets).

assets are situated below the efficient frontier, meaning that it is always inefficient to invest in a single asset. Once again, point Y represents the lowest achievable risk. Combinations below point Y are also inefficient as a higher return can be generated with the same amount of risk. Point Z reflects, as above, the point of the highest return-risk efficiency.

3. Portfolio theory of circular resource use

Overall, portfolio theory reflects an intrinsic relationship between return and risk, with the assumption that whilst return is desirable, risk is undesirable. To achieve higher returns, however, investors must embrace higher risks. Portfolio theory assists investors in demonstrating how they can maximize the return generated for a given level of risk.

We can apply these principles to the arena of natural resource use. In short, we need natural resources, such as minerals or precious metals for example, to generate a return — something that we can now think of as products or services. A higher return is usually preferable to a lower return, whilst a lower use of natural resources is preferable to a higher use of natural resources. In other words, whilst society demands more products in the modern age, it does so whilst being mindful of the finite natural resources on 'spaceship earth' (Boulding, 1966), as we have argued. Analogously to financial contexts, resource users ('investors') are encouraged to use resources efficiently, i.e. to maximize the return for a given amount of natural resources — or to minimize the amount of natural resources used for a given return. This efficiency of natural resource use is also referred to as eco-efficiency (Manzini, 1993; World Business Council for Sustainable Development, 1996).

As we have also argued, the circular economy is one avenue towards eco-efficiency. In a fully circular economy, i.e. where no resources are wasted, eco-efficiency reaches infinity (Figge et al., 2017). Despite their increasing popularity (Korhonen et al., 2018), fully circular systems remain a purely conceptual proposition. In practice, iron is currently used 2.67 times (Daigo et al., 2005), for example, copper 1.9 times (Eckelman and Daigo, 2008), and nickel 3 times (Eckelman et al., 2012). In a fully circular economy, these resources would be used an infinite number of times. We can therefore assume that at least some of the resource flows are neither fully linear nor fully circular today.

Whilst a single firm can adopt systems to use its resources circularly, circular economy systems can also span several different firms, such as those seen in industrial symbiosis (e.g. Chertow, 2000a; Fan et al., 2021; Lu et al., 2021). By forming collaborative groups, within which resources flow back and forth between resource users, these groups need fewer resources. We argue that there is a parallel between the effect of diversification in finance and the resource-reducing effect of circular economy systems in general and industrial symbiosis in particular: Risks are reduced in financial contexts by building a portfolio of assets; the use of natural resources are reduced in the circular economy by building a portfolio of collaborating resource users.

To unpack our argument further, we first apply portfolio theory to resource use with the example of a group of 2 resource users (A and B). Both A and B use a natural resource (X) to generate a return (R). For simplicity, we assume that each resource user either produces a homogeneous good, or that each return is measured in the same physical or monetary unit. The ratio of R to X reflects the eco-efficiency of each resource user. In using 10 units of natural resources, resource user A sees a return of 100 units, with an eco-efficiency therefore of 10. In contrast, B uses 20 units of natural resources that generate a return of 250 units, with an eco-efficiency therefore of 12.5.

We assume that similar to investments into assets, resources can be given fully or partially to different resource users. The return of a portfolio of resource users A and B corresponds to the weighted average of the return of resource users A and B.

$$\text{Portfolio } return = x_a{}^*r_a + x_b{}^*r_b$$

with:
x_a: Percentage allocated to resource user A
x_b: Percentage allocated to resource user B
r_a: return of resource user A
r_b: return of resource user B

Analogously to calculating portfolio risk, as above, we can use a matrix to calculate the resource use of the group, or portfolio, as we demonstrate in Table 2. Here, the amount of natural resources used corresponds to the square root of the sum of the four boxes (AA, AB, BA, BB).with:
n_a: Natural resources used by A
n_b: Natural resources used by B
l_{ab}: Circularity coefficient

The circularity coefficient describes the degree of circularity between the two resource users and ranges from +1 (fully linear) to −1

Table 2
Covariance matrix illustrating the natural resource use of AB.

	A (x_a, n_a)	B (x_b, n)
A (x_a, n_a)	$x_a{}^{2*}\ n_a{}^2$	$x_a * x_b * l_{ab} * n_a * n_b$
B (x_b, n_b)	$x_a * x_b * l_{ab} * n_a * n_b$	$x_b{}^{2*}\ n_b{}^2$

(fully circular). In practice, resource use is usually neither fully linear nor fully circular. The circularity coefficient shows where resource use is positioned on the continuum between full linearity and full circularity.

The use of natural resources on the portfolio level, therefore, corresponds to:

$$\text{Natural resources} = \sqrt{x_a^2{*}n_a^2 + x_b^2{*}n_b^2 + 2(x_a x_b l_{ab} n_a n_b)}$$

We now distinguish between three different manifestations of linearity and circularity: Those which are fully linear; those which are fully circular; those which are imperfectly circular. As before, researchers have argued that a group level approach to circularity yields a rather different insight into the effectiveness of circularity (e.g. Figge et al., 2021). As such, resource use can only be determined as *potentially* circular instead of assumed. Products, for example, that consist of components that are all recyclable — which could contribute in theory to a circular system, via circular resource flows — only contribute in reality when such recyclables are taken back from consumers and reused again. Thus, the coefficient of circularity represents a *potential* circularity. This is analogous to the covariance between different assets in portfolio theory; if investors do not use the information to diversify, but concentrate their investments on a single asset, risk cannot be diversified away.

Fig. 3 reflects the return and resource use of the two resource users (A and B). Line 1 reflects fully linear resource use and indicates the overall return-resource use characteristics when resources are given to either A or B or to combinations of A and B. Both return and resource use represent the weighted average of the resource use of A and B. Line 2 reflects circular resource use and indicates more efficient combinations of return and resource use when resources are allocated to both A and B. By carefully allocating resources to A and B, i.e. in a way that foregrounds goals of eco-efficiency, resource use can even become fully circular, i.e. resource use on the portfolio level becomes zero — at least in theory.

Line 3, representing a circularity coefficient of 0, is perhaps the most thought-provoking, as this reflects a resource use that is neither fully linear nor fully circular, but something between the two. Two points are of particular interest. At point Y we use 8.94 units to produce a return of 130 units. This is achieved when 80% of resources have been allocated to A and 20% to B. At this point the portfolio of resource users A and B reaches its minimum resource use. If we were to allocate more resources to A and less to B overall resource use would increase and return decrease, which is undesirable. If we allocate more resources to B and less to A both resource use and portfolio return increase. This leads us to the second point. The highest efficiency is reached at point Z, with an efficiency of 16 (calculated by a return of 157 divided by a resource use of 9.8). It is worth noting that the efficiency of the portfolio exceeds the individual efficiencies of both A, (having an efficiency of 10) and B (having an efficiency of 12.5), pointing to the advantages of circular resource use in this way.

As we have argued, in practice it is very likely that portfolios — of financial assets or circular resource users alike — consist of more than two constituents. Thus, we now explore how eco-efficiency unfurls via circular resource use within a group consisting of four resource users as an example.

By increasing the number of resource users we also increase the number of possible combinations. Return and resource use can be calculated analogously to our previous worked example of two resource users. The return on the portfolio level remains the weighted average of the returns of all individual resource users collectively. Resource use at the portfolio level can be calculated using the same matrix used before, i.e. again in reference to our example of two resource users; for the case of n resource users the size of the matrix increases to $n{*}n$. Thus, for the scenario of four resource users, we can simply add two more to the aforementioned resource users A and B. In this example, resource user C creates a return of 40 with 5 resource units (with an eco-efficiency of 8), and resource user D uses 15 resource units to create a return of 150 (with an eco-efficiency of 10). We assume that the coefficient of circularity between all resource users is zero, with resource use, therefore, being imperfectly circular.

Using the same principle as per two resource users, we can calculate the return and the resource use of different combinations of resources allocated to the four resource users. In contrast to the case of two resource users, however, we are not interested in all combinations; only those that offer the highest possible return for a given level of resource use. In financial portfolios, these combinations that offer the highest possible return for a given level of risk are referred to as efficient

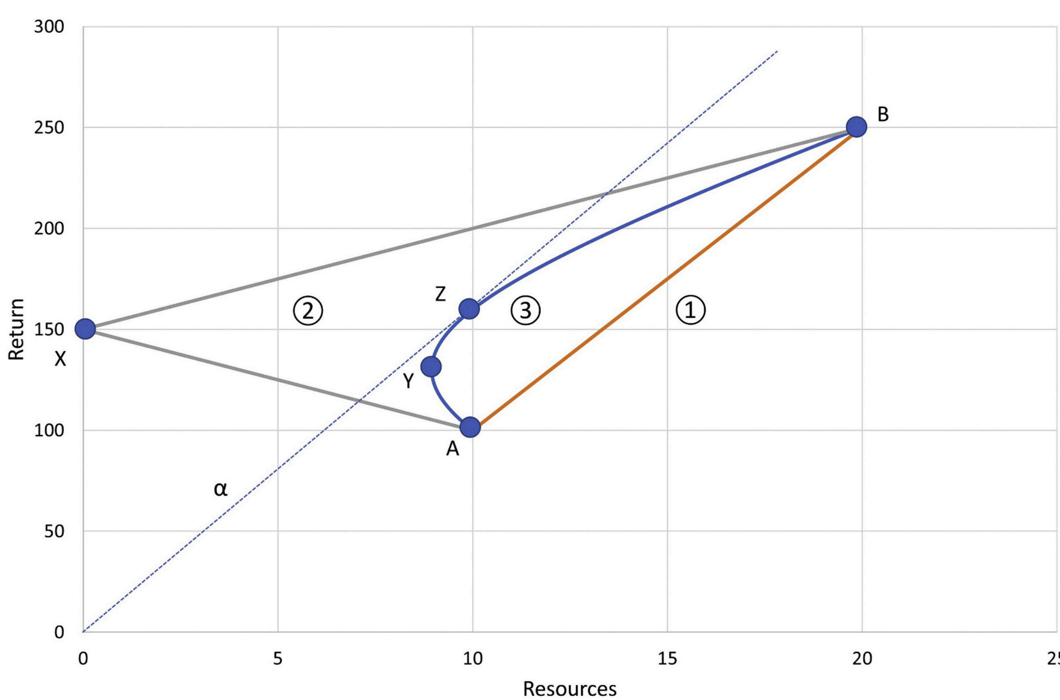

Fig. 3. A circular portfolio consisting of two firms.

(Markowitz, 1952). Analogously, we refer to these combinations as 'circularly efficient'.

Fig. 4 depicts circular efficiency as it unfurls in a group of four resource users. The curved line signifies all circularly efficient combinations. The straight line (α) that is tangent at point Z identifies the combination with the highest resource efficiency. Point Y shows the point of lowest resource use. All resource users but one (B) are below the line of circular efficiency. This indicates that the efficiency of resource use — obtained by a combination of users for a given level of resource use — is always higher when users cooperate than when they operate in isolation. The reason why resource user B lies on the line of circular efficiency is that the only possibility to use 20 units of resources is by allocating all resources to this user.

4. Discussion

At the crux of our contribution, we argue that portfolio theory generates valuable insights into the circular economy. These pivot first on the drivers of circularity, and second, the governance of resources; the threads of 'levels', 'risk', and 'rewards' — as key components of financial portfolio theory — run through these insights. We unpack our discussion as follows, before outlining some suggestions for further research.

4.1. Drivers of circularity

Using resources efficiently is a necessary condition for using resources sustainably. A fully, or perfect, circular use of resources promises infinitely high resource efficiency (Figge et al., 2017). However, perfect circularity, for one reason or another, is somewhat of a quixotic notion (Daigo et al., 2005; Eckelman and Daigo, 2008; Eckelman et al., 2012). While it is clearly desirable to aim for higher circular resource use, we argue that scholars must remain realistic on whether full circularity can be achieved in practice. As such, we argue there is a need for researchers to address the arguably more plausible scenario of imperfect circular systems of resource use.

In a recent article in this journal, Figge et al. (2021) suggest that collating individual resource users' activities to determine the extent to which resources are used circularly at the macro level, generates misleading conclusions. In reality, resources are frequently exchanged *between* resource users — one example being the industrial symbiosis system of Kalundborg (Ehrenfeld and Gertler, 1997). By using resources symbiotically within a group of users, the benefit occurs — and can be observed — at the level of the group, rather than that of the individual. The portfolio view shows how different combinations of resource use across different users lead to differing extents of resource use and eco-efficiency.

We identify three variables that help determine the eco-efficiency of resource use at the macro-level — or as we equate it in this paper, the 'societal' level. First, higher efficiency at the micro-level leads to higher efficiency at the portfolio level. Second, the closer the coefficient of circularity between resource users is to -1, the higher the degree of circularity at the portfolio level. Third, the allocation of resources to individual users within the portfolio impacts the efficiency of resource use. In other words, within every 'portfolio', i.e. group, there is an optimal combination of resource users — in terms of its impact on eco-efficiency of resource use on the portfolio level.

However, rather than being standalone components, it is the interplay between these variables that helps determine resource use efficiency at the macro level. Essentially this challenges the idea that perfect circularity (with a circularity coefficient of -1) — even if it were viable in practice — automatically maximizes circularity, and correspondingly, eco-efficiency. Put simply, a situation where resource users reuse and recycles less can lead to a higher circularity than a situation where they reuse and recycle more. Although our challenge seems counterintuitive, the analogous and very much established argument from a financial context, suggests otherwise: Only a very specific portfolio of assets minimizes or even eliminates risk.

As a starting point of exploring these three variables in more detail, and particularly the interplay between them, we reassert Figge et al.'s (2021) argument that macro-level efficiency cannot be derived — or at least guaranteed — from merely maximizing efficiency of resource use at the individual firm level. As we intimate above, the relationship between micro- and macro-level efficiency is moderated by the coefficient of circularity, as well as the optimal distribution of resources across individual firms. As the examples in Figs. 3 and 4 indicate, when resource use is not linear, minimum resource use as well as maximum

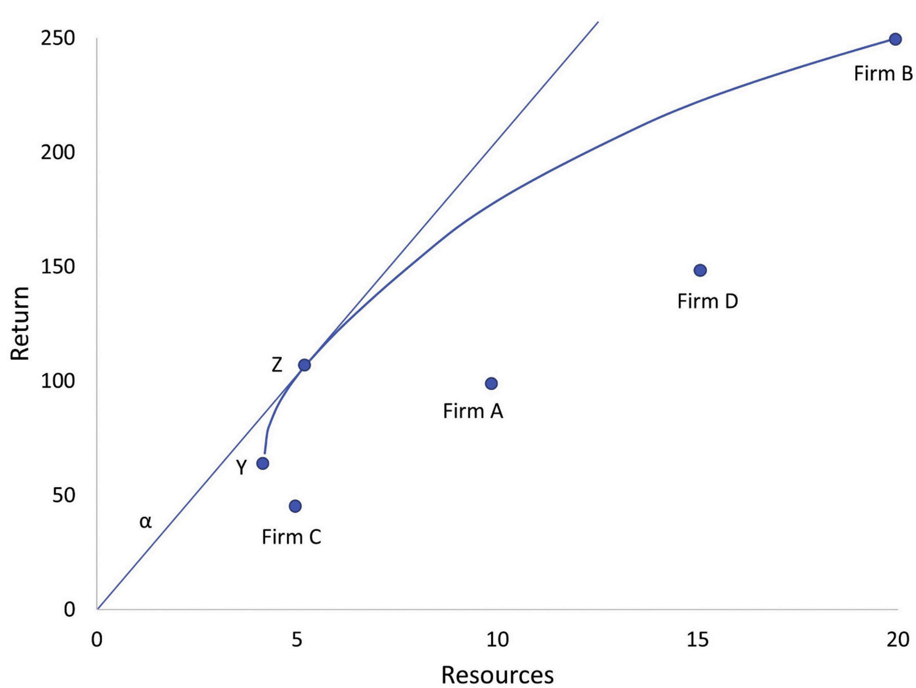

Fig. 4. Circular portfolios (4 firms).

efficiency (which do not necessarily coincide) are obtained through an optimal combination of micro-level resource uses. In other words, whilst the coefficient of circularity plays a particularly central role, in that it reflects the degree to which resources are potentially reused by another resource user, it is only with the 'right' combination of resource users that the circularity materializes. For example, having a circularity coefficient of −1 — signaling full, or perfect, circularity — only results in full circularity when there is a desirable combination of resource users. If firms that want to use pre-used resources but cannot do so because no others are willing to provide such resources, then they cannot contribute to circularity — despite their willingness to do so. Similarly, firms that make their used resources available can only contribute to systems of circularity if there are other willing and able to receive such resources. As Fig. 3 shows there is only one particular point (point X) where resource use is theoretically fully circular. A fully circular use of resources, therefore, requires not only a circularity coefficient of −1, but also an optimal combination of resource users that interact to ensure no waste is generated.

Returning to our starting point, our application of portfolio theory reveals further support for the argument that the sum of individual firm circularity cannot determine the extent of circular resource use at the macro-level. Specifically, by examining Figs. 3 and 4, we show that when there are more firms with a low coefficient of circularity, resource use efficiency is higher at the level of the portfolio level. Line 3 of Fig. 3 represents a portfolio of two firms (A and B), with a circularity coefficient of zero. Fig. 4 illustrates a portfolio of four firms (A, B, C, D), also with a circularity coefficient of zero. Firms A and B have identical characteristics in both portfolios. The efficiencies of firms C and D, 8 and 10 respectively, that have been added in Fig. 4 are below or at the same level as the efficiencies of firms A and B, which are 10 and 12.5 respectively. Interestingly, the maximum efficiency increases from 16 in Figs. 3 to 20.5 in Fig. 4. Put differently, by adding firms with a low efficiency, the efficiency of resource use increases.

4.2. Governance of resource use

Switching to a slightly different track, a portfolio view on the circular use of resources also generates insights into the governance of resource use in the circular economy in several ways.

The first insight from the application of portfolio theory concerns the circumstances that might demand a reward for using natural resources, in contrast to those which do not. Markowitz's (1952, 1959) theory gave rise to the capital asset pricing model (CAPM) (Lintner, 1965a, 1965b; Mossin, 1966; Sharpe, 1964), which enables risk to be 'priced'. In the context of investors, the price of risk equates to the amount of return they can expect for assuming the risk attached to a specific investment. From the perspective of companies, it is the amount of return they need to offer in return for the risk they generate. The CAPM further makes an important distinction between systematic and unsystematic risk. The latter — in contrast to the former — can be diversified away at the portfolio level. Subsequently, there is also no reason to 'reward' investors: If there is no risk, the lure of a reward is not needed. In contrast, and by using similar logic, systematic risk needs to be rewarded, as it cannot be diversified away.

The same reasoning can be applied to the context of natural resources. Owing to the scarcity of virgin resources (Figge et al., 2017), their use is undesirable for society, creating the potential need for a reward (a return) to make their use more acceptable. For instance, some countries have devised sector or geographical based plans for carbon-neutrality (e.g. Dahal et al., 2018; Dong et al., 2021b; Griffiths and Sovacool, 2020; Ren et al., 2021) to which the circular economy could inadvertently contribute: Less mining — and consequently less energy and water intensive processes — means that we potentially use more secondary materials. Assuming that this is socially desirable change, a reward is needed to persuade firms, policymakers, and so on, that converse behavior is acceptable. However, whether this reward is needed depends somewhat on the extent to which resources are used circularly. In perfectly circular systems, no reward is needed, as no new resources are used by firms, whether they be singular or grouped together within such a system. In perfectly linear systems, rewards are almost certainly needed to rationalize their use. However, as we have argued, imperfect circular systems are more realistic in practice, with coefficients of circularity that sit somewhere between perfectly circular and linear systems.

The second (related) insight garnered from portfolio theory delves more deeply into the distinction between systematic and unsystematic risk, and specifically how it signifies that the distinction between the individual and portfolio/group levels in determining extents of circularity and eco-efficiency is important.

In finance, we cannot distinguish between systematic and unsystematic risk solely at the individual level. To distinguish between the two kinds of risk, we must refer to the portfolio level. In finance, this equates to two different methods. Either we examine the covariance of returns with other individual stocks (Markowitz, 1952, 1959), or we look at beta — the extent to which a stock covaries with the entire market of stocks (Lintner, 1965a, 1965b; Mossin, 1966; Sharpe, 1964). Put differently, whether a risk is systematic or unsystematic is context-dependent. In isolation, there is only one kind of risk, total risk, at the individual level.

The discussion on these differing dimensions of risk at the individual and the portfolio level is well established in finance. In reality, most investors can diversify, meaning that only systematic risk is relevant. In contrast, for investors whose interests are tied to an individual firm, total risk, i.e. systematic *and* unsystematic risk, is relevant. This is often the case in the context of managers acting within firms. The long-standing assumption is that firms should be managed in ways that foreground the interest of their owners, i.e. to create shareholder value (Rappaport, 1986), binding managerial action to outcomes for organizations and their owners (Donaldson, 1963). However, this dynamic comes at a cost. As Lypny (1993, p. 208) argues, "when managers are unable to fully diversify their personal portfolios because their human capital is specific to their jobs and to the firms for which they work", then their personal interests and the interests of shareholders diverge. Thus, whilst managers are interested in reducing total risk, shareholders are primarily interested in reducing systematic risk, as the former are intrinsically tied to a single firm, whereas the latter are commonly not. The crux of the problem is that assuming risk is frequently linked to the promise of a reward, as we have already outlined. Thus, by reducing total risk, managers endanger rewards that are risk-free to shareholders.

In applying the same principle to linear and circular systems of resource use, we can assume that resources — whether virgin or pre-used — constitute a burden. A lower burden is clearly preferable to a higher burden. We can assume that it is within the interest of individual resources users to lower total resource use. This is because using resources is linked to costs, and resource users are keen to reduce costs. This is not necessarily useful from the perspective of the overall portfolio. Each resource user in reducing its consumption might individually benefit. However, this might remove the opportunities that their 'waste' resources generate for other resource users. Simply put, reducing resource use might be advantageous for individual users, but disadvantageous for their collaborators, decreasing rather than increasing eco-efficiency in the process — at the group level. This is in-line with the argument brought forward by (Figge et al., 2021), who use group selection (Griffing, 1967; Wilson, 1975) to show how a group of individually less efficient individuals can form a more efficient group of resource users. This raises questions about how resource use is governed.

4.3. Further research

Whilst we offer a theoretical analysis, we encourage empirical work to test our argument as a first, and rather obvious, need for further research. Second, whilst our model describes the foundations of our argument, arguably in practice — as (different and multiple) resources move through additional cycles of use, re-use, re-re-use, etc. — portfolios increase in complexity. Further work, therefore, could explore how our model might develop in light of such intricacies. There are implications for the optimization of portfolio size, for instance: In portfolio theory, there is trade-off between the additional benefits of further diversification and transaction costs. How this notion might be applied to our model, therefore, could be interesting to explore. Third, whilst our model indicates an optimal combination of resource users, *how* society organizes circular systems to generate such optimization might be fertile ground for further work. More generally, some countries such as China have specific socioeconomic conditions and tend to scope circular economy systems and indicators that include other environmental concerns such as pollution (McDowall et al., 2017), and it might be useful for scholars to consider how these factors might be enfolded in to our model, especially at a policy level. More specifically, we have pointed to the tension in financial portfolio theory, for example, between shareholders who can diversify and managers who cannot, and so questions remain as to how we can move towards systems that are organized at the group (portfolio) level in practice that favor circular resource use. Agency theory (Jensen and Meckling, 1976) might be a good starting point to explore this idea in more depth. Finally, and perhaps most importantly, might be subsequent investigations into how we can measure the outcomes of circularity in the clustered organizational configurations that we suggest here. The debate amongst scholars on which indicators best capture eco-efficiency in this sense is well-established, but a shift away from the individual firm towards group level activity potentially demands a rethink on the utility of the indicators currently in use — especially those which are focused on measuring circularity at the level of the firm. Important work recently published in this journal illustrates the point: Fraccascia et al. (2021) describe, how the eco-efficiency derived from industrial symbiosis, for example, needs specific indicators that emphasize the eco-system of firms as a whole. Further work, therefore, could explore the implications of our theory for the development of appropriate indicators.

5. Conclusion

Portfolio theory is an established framework within the finance literature and has been a mainstay for explaining the dynamics between risk and return of assets for decades. In applying this theory to the circular economy, we have garnered insights into eco-efficiency.

By using a portfolio lens to examine the circular economy, we have shown that an increase in the circularity of resources does not necessarily mean that resources will be used more efficiently: The combination of resource users that minimizes resource use is not necessarily the combination that maximizes eco-efficiency. The idea that the circular economy results in infinite eco-efficiency of resource use is therefore only valid in the improbable case of perfect circularity. This points to the importance of distinguishing between the theoretical concept of perfect circularity and the practical case of an imperfectly circular use of resources. It is this latter case that existing research fails to address and that the portfolio view on the circular economy contributes to in particular.

Further, we build on recent work that challenges the notion that adding together the eco-efficiencies of individual firms, determines the extent of eco-efficiency at a macro-, or societal level. Drawing on portfolio theory, we have identified three variables that are crucial in understanding circularity at macro levels: We demonstrate that the portfolio (or group) level is more conducive than a focus on activity that unfurls purely at an individual level; we highlight the relevancy of the coefficient of circularity; and we emphasize the impact of the 'right' mix of firms within the portfolio (or group). In addition, we argue that portfolio theory — and specifically concepts of risk and return — generates insights into the governance of natural resources.

Whilst we offer a novel, but insightful take on the circular economy, our argument is embryonic in that there is scope for further research to deepen and expand on the use of portfolio theory to understanding the circular economy's various facets. We hope that other researchers will join us in this endeavor.

Declaration of Competing Interest

The authors are not aware of any conflicts of interest.

Acknowledgements

This research has benefited from the support of Frank's Per and Eivor Wikström Guest Professorship at Umeå University and the Circular Economy & Sustainable Business Models Chair at ESCP Business School.

References

Bajaj, S., 2021. Interplay of Equity Shares: Allocating Investments via Markowitz Model. IUP J. Appl. Financ. 27.
Bauwens, T., Hekkert, M., Kirchherr, J., 2020. Circular futures: what will they look like? Ecol. Econ. 175, 106703.
Boulding, K., 1966. The Economics of the Coming Spaceship Earth, New York. Jarrett, H., Baltimore, pp. 3–14.
Brealey, R.A., Myers, S.C., Allen, F., 2020. Principles of Corporate Finance, 13th Edition. McGraw-Hill Education, New York, NY.
Chertow, M.R., 2000a. Industrial symbiosis: literature and taxonomy. Annu. Rev. Energy Environ. 25, 313–337.
Chertow, M.R., 2000b. The IPAT equation and its variants. J. Ind. Ecol. 4, 13–29.
Commoner, B., 1972. The environmental cost of economic growth. In: Ridker, R.G. (Ed.), Population. Resources and the Environment. Government Printing Office, Washington, DC, pp. 339–363.
Dahal, K., Juhola, S., Niemelä, J., 2018. The role of renewable energy policies for carbon neutrality in Helsinki metropolitan area. Sustain. Cities Soc. 40, 222–232.
Daigo, I., Matsuno, Y., Ishihara, K.N., Adachi, Y., 2005. Development of Methodology for Analyzing the Average Number of Times of Use and the Average Residence Time of Iron Element in Society by Applying Markov Chain Model Tetsu-to-Hagané, 91, pp. 159–166.
DeSimone, L.D., Popoff, F., 1998. Eco-efficiency. The Business Link to Sustainable Development, 2nd printing. Ed. MIT Press, Cambridge, Mass.
Donaldson, G., 1963. Financial goals: management vs. stockholders. Harv. Bus. Rev. 41, 116–129.
Dong, H., Zhang, L., Geng, Y., Li, P., Yu, C., 2021a. New insights from grey water footprint assessment: an industrial park level. J. Clean. Prod. 285, 124915.
Dong, L., Miao, G., Wen, W., 2021b. China's carbon neutrality policy: objectives, impacts and paths. East Asian Policy 13, 5–18.
Eaton, M.J., Yurek, S., Haider, Z., Martin, J., Johnson, F.A., Udell, B.J., Charkhgard, H., Kwon, C., 2019. Spatial conservation planning under uncertainty: adapting to climate change risks using modern portfolio theory. Ecol. Appl. 29, e01962.
Eckelman, M.J., Daigo, I., 2008. Markov chain modeling of the global technological lifetime of copper. Ecol. Econ. 67, 265–273.
Eckelman, M.J., Reck, B.K., Graedel, T., 2012. Exploring the global journey of nickel with Markov chain models. J. Ind. Ecol. 16, 334–342.
Eder, A., Salhofer, K., Scheichel, E., 2021. Land tenure, soil conservation, and farm performance: an eco-efficiency analysis of Austrian crop farms. Ecol. Econ. 180, 106861.
Ehrenfeld, J., Gertler, N., 1997. Industrial ecology in practice: the evolution of interdependence at Kalundborg. J. Ind. Ecol. 1, 67–79.
Ekins, P., Hughes, N., 2017. Resource Efficiency: Potential and Economic Implications. A Report of the International Resource Panel. UNEP.
Elia, V., Gnoni, M.G., Tornese, F., 2017. Measuring circular economy strategies through index methods: a critical analysis. J. Clean. Prod. 142, 2741–2751.
Fama, E.F., 1970. Efficient capital markets: a review of theory and empirical work. J. Financ. 25, 383–417.
Fama, E.F., MacBeth, J.D., 1973. Risk, return, and equilibrium: empirical tests. J. Polit. Econ. 81, 607–636.
Fan, Y.V., Varbanov, P.S., Klemeš, J.J., Romanenko, S.V., 2021. Urban and industrial symbiosis for circular economy: Total EcoSite integration. J. Environ. Manag. 279, 111829.
Figge, F., Givry, P., Canning, L., Franklin-Johnson, E., Thorpe, A., 2017. Eco-efficiency of virgin resources: a measure at the interface between micro and macro levels. Ecol. Econ. 138, 12–21.
Figge, F., Thorpe, A.S., Givry, P., Canning, L., Franklin-Johnson, E., 2018. Longevity and circularity as indicators of eco-efficient resource use in the circular economy. Ecol. Econ. 150, 297–306.
Figge, F., Thorpe, A., Good, J., 2021. Us before me: a group level approach to the circular economy. Ecol. Econ. 179, 1–8.
Fraccascia, L., Giannoccaro, I., Albino, V., 2021. Ecosystem indicators for measuring industrial symbiosis. Ecol. Econ. 183, 106944.
Fuss, M., Barros, R.T.V., Poganietz, W.-R., 2021. The role of a socio-integrated recycling system in implementing a circular economy – the case of Belo Horizonte, Brazil. Waste Manag. 121, 215–225.

Geng, Y., Sarkis, J., Ulgiati, S., Zhang, P., 2013. Measuring China's circular economy. Science 339, 1526–1527.
Geng, Y., Sarkis, J., Bleischwitz, R., 2019. How to Globalize the Circular Economy. Nature Publishing Group.
Ghisellini, P., Cialani, C., Ulgiati, S., 2016. A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. J. Clean. Prod. 114, 11–32.
Graedel, T.E., 1996. On the concept of industrial ecology. Annu. Rev. Energy Environ. 21, 69–98.
Griffing, B., 1967. Selection in reference to biological groups I. Individual and group selection applied to populations of unordered groups. Austra. J. Biol. Sci. 20, 127–140.
Griffiths, S., Sovacool, B.K., 2020. Rethinking the future low-carbon city: carbon neutrality, green design, and sustainability tensions in the making of Masdar City. Energy Res. Soc. Sci. 62, 101368.
Jensen, M.C., Meckling, W.H., 1976. Theory of the firm. Managerial behavior, agency costs and ownership structure. J. Financ. Econ. 3, 305–360.
Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232.
Korhonen, J., Honkasalo, A., Seppälä, J., 2018. Circular economy: the concept and its limitations. Ecol. Econ. 143, 37–46.
Lintner, J., 1965a. Security prices, risk and maximal gains from diversification. J. Financ. 20, 587–615.
Lintner, J., 1965b. The valuation of risk assets and the selection of risky Investments in Stock Portfolios and Capital Budgets. Rev. Econ. Stat. 47, 13–37.
Lu, C., Pan, X., Chen, X., Mao, J., Pang, J., Xue, B., 2021. Modeling of waste flow in industrial symbiosis system at City-region level: a case study of Jinchang, China. Sustainability 13, 466.
Lypny, G.J., 1993. An experimental study of managerial pay and firm hedging decisions. J. Risk Insurance 60, 208–229.
Manzini, E., 1993. Designing Eco-Efficiency and Getting Eco-Efficient. Business Council for Sustainable Development, Geneva, Switzerland.
Markowitz, H.M., 1952. Portfolio selection. J. Financ. 7, 77–91.
Markowitz, H.M., 1959. Portfolio Selection. Efficient Diversification of Investments. Wiley & Sons, New York, NY.
McDowall, W., Geng, Y., Huang, B., Barteková, E., Bleischwitz, R., Türkeli, S., Kemp, R., Doménech, T., 2017. Circular economy policies in China and Europe. J. Ind. Ecol. 21, 651–661.
Mossin, J., 1966. Equilibrium in a capital asset market. Econometrica 34, 768–783.
Parchomenko, A., Nelen, D., Gillabel, J., Rechberger, H., 2019. Measuring the circular economy - a multiple correspondence analysis of 63 metrics. J. Clean. Prod. 210, 200–216.
Pearce, D., Turner, R.K., 1990. Economics of Natural Resources and the Environment. Johns Hopkins Univ. Press, Baltimore.
Rappaport, A., 1986. Creating Shareholder Value. The New Standard for Business Performance. The Free Press, New York.
Ren, L., Zhou, S., Peng, T., Ou, X., 2021. A review of CO2 emissions reduction technologies and low-carbon development in the iron and steel industry focusing on China. Renew. Sust. Energ. Rev. 143, 110846.
Shakespeare, W., 1750. The Merchant of Venice. J. and P, Knapton, London.
Sharma, L., Pandey, S., 2020. Recovery of resources from end-of-life passenger cars in the informal sector in India. Sustain. Product. Consump. 24, 1–11.
Sharpe, W.F., 1964. Capital asset prices. A theory of market equilibrium under conditions of risk. J.Finance 19, 425–442.
Stevenson, R.S., Evans, J.W., 2004. Editorial to: cutting across interests: cleaner production, the unified force of sustainable development. J. Clean. Prod. 12, 185–187.
Ünlü, R., Xanthopoulos, P., 2021. A reduced variance unsupervised ensemble learning algorithm based on modern portfolio theory. Expert Syst. Appl. 180, 115085.
Wilson, D.S., 1975. A theory of group selection. Proc. Natl. Acad. Sci. 72, 143–146.
World Business Council for Sustainable Development, 1996. Eco-Efficiency and Cleaner Production: Charting the Course to Sustainability. WBCSD, Geneva.
World Business Council for Sustainable Development, 2000. Eco-Efficiency. Creating More Value with Less Impact. WBCSD, Geneva.
Zeng, D.Z., Cheng, L., Shi, L., Luetkenhorst, W., 2021. China's green transformation through eco-industrial parks. World Dev. 140, 105249.