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ORIGINAL ARTICLE

Are important phenomena of joint production still being neglected by economic theory? A review of recent literature

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Abstract

Joint production is a term with a long history in economics, encompassing a variety of ubiquitous production types that usually generate both main products as well as desirable and undesirable byproducts. However, studies in economic history show that important phenomena subsumed under this term were largely ignored by the theories of general economics and of business economics in the twentieth century. Our systematic, narrative literature review based on the Web of Science analyses the extent to which this and other terms corresponding to such phenomena have been taken up by researchers since then. Whereas the number of papers on undesirable outputs has soared, especially in the past decade, the economic literature regarding joint production and harmless byproducts is much smaller and hardly growing. This is in stark contrast to their relevance in practice, recorded in the non-economic literature. Harmful byproducts result from coupled production, as a rule. However, this important manifestation of joint production is usually not distinguished from other specific types. In German-language literature, coupled production is defined as a kind of (truly) joint production in which an intended product cannot be manufactured without an additional type of output under consideration. Our review reveals a lack of clarity, precision, and consistency in the use of established terms and concepts in English-language literature, that may lead to insufficient external validity of widely accepted models. Moreover, one gets the impression that academic disciplines concerned with business or general economics focus too much on problems that are currently of economic interest, while neglecting other issues that may be marginal today but are likely to be of critical importance in the near future.

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1 Introduction

The quality of any theory crucially depends on the clarity, precision, and consistency of its basic concepts and terms. Joint production is a prominent basic notion since the early days of economics. In his insightful historical review, Kurz (1986, p. 11) points out that it was a main subject of essays and intensive discussions by influential classical and early neoclassical economists, even before the nineteenth century:

> Numerous examples of joint production and joint costs are reported in the early literature on husbandry, estate management and farming, in the writings of the mercantilists and physiocrats. This is hardly surprising since the then most important sector of the economy and the major object of the analysis, i.e. agriculture, appears to be characterised by universal joint production. However, it was not until Adam Smith's *Wealth* that an attempt was made to transcend the purely descriptive treatment of the problem and to begin to deal with it in analytical terms. Therefore, Smith's contribution is the starting point of our historical inquiry.

From that enquiry, Kurz (1986, p. 34) concludes that the "problem of joint production played a significant role in the evolution of economic thought since the advent of the classical school. In view of the empirical examples provided it is perhaps possible to confirm Jevons's contention that joint production is the general case" (and not a peculiar case). The analysis of joint production contributed to the abandonment of the classical in favour of the neoclassical theory of value.

Thereafter, though, important phenomena that are closely related to joint production were largely ignored. Studies in economic history by Baumgärtner (2000) and Dyckhoff (2022) demonstrate that general economics as well as business economics did not only neglect undesirable outputs and other byproducts during the twentieth century, at least until the 1980s, but also even important cases of multiple joint (main) products. Because of the damages to the ecosystems of planet Earth, especially regarding climate change as 'greatest market failure in history', undesirable byproducts have become of central interest to our civilisation in recent decades, and consequently to several academic disciplines, too. Therefore, the purpose of our paper is to investigate to what extent the academic research of the past decades, particularly regarding business, management, and economics, has taken up the three subjects of joint production, byproducts, and undesirable or 'bad' outputs by using these or similar (technical) terms.

There are different manifestations of joint production, which are seldom clearly delineated from each other and will be characterised in more detail later in this paper. For now, *joint production* in general denotes a production process which

transforms inputs into two or more distinct types of output. In principle, two basic kinds of joint outputs can be differentiated, namely (main) products on the one hand and byproducts on the other. A *main product* is of a type of output that is intended, i.e., it is the result of a process which is established and continued with the purpose to obtain certain quantities of this output. Thus, each type of main product is desired, however only so long as it is not produced in abundance, in which case its surplus would be superfluous or waste. On the contrary, a *byproduct* is of a type of considered joint outputs which is unintended, i.e., produced without purpose (e.g. trim loss). It may either be desirable too, e.g., because it might generate some revenue when it is sold, or else be an *undesirable* (or *bad*) *output*, usually because of its negative impacts on natural, social or other environments.[1] Whether an output is a main product or a byproduct and whether it is desirable or undesirable, or even not considered at all, depends on the perceptions, intentions, and preferences of the acting human beings and may change in the course of time, e.g. due to new legislation, innovation, or a different environment.

The present paper will focus on the following research questions regarding these joint production-related terms:

- Are there any literature surveys which include the respective term in their topics? How many respective scientific articles have been published in the past decades? What is their development over time? How often are they cited? Which journals contain most of the relevant literature? Which articles are cited most frequently, and which authors are most prevalent? What kind of questions and issues are dealt with by these articles?
- How were the subjects and their corresponding terms discussed over time, and what kind of relations are there between them and the journals in which they were published, the authors who wrote about them, as well as the special questions and issues dealt with? Are important phenomena of joint production still being neglected by general and by business economic theory in the recent literature? How can this be changed?
- Bearing the historical background of the term joint production in mind, which conclusions can be drawn from the results of this study for important future research paths, especially regarding business and general economics?

The next parts of this paper are structured as follows: Sect. 2 describes the methodology of the literature study, while Sect. 3 presents and explains resulting main

[1] This fundamental distinction of main products from byproducts is in accordance with Max Weber's (1921) two criteria of 'ends' and 'secondary results' which together with the 'means' form the three categories determining the *purposive rationality* of an action or of an actor. The term 'ends' is used to name the purposes which constitute the original motives for the action considered in the situation at hand. The extent to which these main ends are achieved determines the *effectiveness* of an action, whereas the consideration of the ends in relation to the means as well as to the secondary results (or side-effects) appraises its *efficiency*. Waste and emissions are examples of undesirable secondary results, whereas a surprising discovery or invention made during an exploration process may be desirable (Dyckhoff and Souren 2022, p. 797).

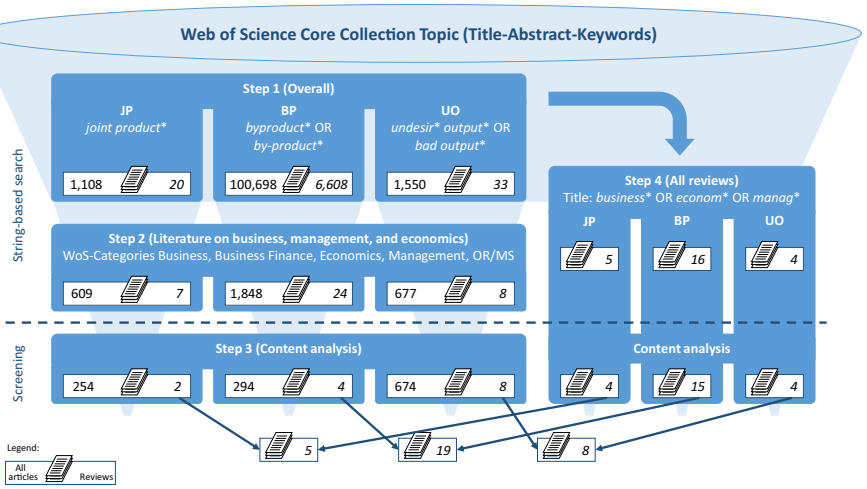

Fig. 1 Search process for relevant literature

facts with respect to the research questions. In Sect. 4, the results are discussed and critically examined, thereby integrating knowledge from several decades of own research and empirical experience as well as findings from related literature. Section 5 draws some important conclusions that indicate relevant paths for future research.

2 Methodology of the literature study

In view of the above research questions, we conducted a systematic narrative literature review.[2] Our purpose is to identify—in a transparent and reproducible way—relevant literature which deals with business, management, or economic aspects of joint production, byproducts, and undesirable outputs by using a corresponding term in the topic. To draw a first map of the field, we focus on a representative collection of relevant sources (not on a comprehensive bibliography of all contributions).

We adopted a four-step approach which is shown by Fig. 1. The literature search was conducted within the Core Collection of the *Web of Science* (WoS) and was subsequently refined. It includes all entries published until the end of 2020.[3] Figure 1

[2] Thus, we follow suggestions of Fisch and Block (2018). For this investigation, only those sources have been considered that had been published in English.

[3] We have made a quick check of more recent publications shortly before submitting the final version of our paper for publication. It shows that the observed trends are also valid until mid-2022. However, it may be pointed out that a special-topic issue on "Proper modelling of production systems that produce both desirable and undesirable outputs" was published by the *Journal of Productivity Analysis* in May 2021 (vol. 55, pp. 155–201). Some parts of our Sect. 4 benefit from an unpublished paper of one of the present authors (Dyckhoff 2021) that comments on the subject of this special issue in general and the statements of its five papers in particular.

presents the schematic analysis via the different search strings[4] within the topics, i.e., showing the relevant terms in the title, abstract or keywords. The screening process assessing the relevance also included a closer look at the whole paper where it seemed useful.

It is necessary to point out a significant restriction here. From our analysis it emerged that the Web of Science did not record abstracts and keywords in its databases until 1990. Therefore, a topic search usually finds older relevant sources only if the search terms are included in the title. This means that the results for the last three decades are not comparable with those before that time. For example, the systematic search procedure did not find the frequently cited, relevant contribution written by Färe et al. (1989) which is titled: "Multilateral productivity comparisons when some outputs are undesirable: a nonparametric approach" (cf. note to Table 5). Nevertheless, this restriction seems to be admissible because we want to review the literature of the past Two decades in the first place. Though, the fact that the early years are underrepresented should be taken into account when interpreting the development over time.

Step 1: For each of the three subjects in question expressed by the terms "*joint product**" (**JP**), *byproduct* OR by-product** (**BP**) and "*undesir* output**" OR "*bad output**" (**UO**) in the topic, the following numbers of entries (including review articles) were identified: JP 1,108 (20), BP 100,698 (6,608), UO 1,550 (33).[5] There are only few overlaps between these terms for the three subjects (including one review by Dakpo et al. (2016) for BP + UO): 35 for JP + BP, 45 for JP + UO, 59 for BP + UO, and 7 for JP + BP + UO.

Step 2: The results identified in Step 1 were then refined by narrowing the pool of results down to literature on business, management, and economics. The Web of Science combines its various *categories* into larger *research areas*. Whereas the category 'Operations Research and Management Science' (OR/MS) builds a research area of its own, the categories 'Business', 'Business Finance', 'Economics', 'Management' are incorporated in one research area, named '*Business (&) Economics'* (Bus/Econ). Selecting those papers which are designated to at least one of the five WoS categories of both areas Bus/Econ and OR/MS results in: JP 609 (7), BP 1,848 (24), UO 677 (8).[6] Due to this thematically expedient restriction, the number of articles decreases compared to Step 1, moderately for JP as well as UO, and significantly for BP. The latter can be explained by the fact that regarding BP most papers in Step 1 belong to the fields of natural or related sciences. Now, there remain following overlaps: 16 for JP + BP, 33 for JP + UO, 39 for BP + UO, and 5 for JP + BP + UO.[7]

[4] The sign * within the search strings indicates that any letter may follow the given *string of letters* in order not to miss sources with a slightly different wording.

[5] Restricting the search to the papers' titles, the following numbers appear: JP 346 (2), BP 13,789 (597), UO 205 (1).

[6] Restricting the search to the papers' titles, the following numbers appear: JP 223 (2), BP 97 (2), UO 97 (1).

[7] The only five articles with all three search terms as topic were published by Zhou and Ang (2008), Kronenberg and Winkler (2009), Mandal and Madheswaran (2010), Färe et al. (2014), and Ray et al. (2018).

Step 3: All sources identified in Step 2 were then filtered regarding their content fit via a closer look at the abstract and, if necessary, the whole text. With JP, a large number of papers had to be omitted because jointness often refers to the combination of production with another activity (e.g. marketing or maintenance) or to the joint (co-)production by several actors. With BP, most articles were excluded, on the one hand because the hyphen in 'by-product*' is partly ignored by WoS such that also all papers containing the text strings 'by product' or 'by production' in title or abstract appeared as results. On the other hand, regarding 'byproduct', the abstracts of most papers in the pool of results point out that byproducts are not the article's research object, but that the term only indicates an additional result of the conducted research process.[8] After these adjustments, the following numbers of representative sources (reviews) remain: JP 254 (2), BP 294 (4), UO 674 (8). Contrary to the other two subjects, the number of papers on UO was not limited by this step due to the fact that (almost) every contribution examines processes that generate outputs (or at least an outcome that in a far-reaching definition is subsumed under this term).

Step 4: Due to the low number of reviews we expanded our search process incorporating those from Step 1 which include one of the following strings in their title: *business** *OR* *econom** *OR* *manag**. Since most of the 149 reviews found this way with BP as topic are very application-specific, we restrict this search in the case of BP to the title. This leads to 25 further reviews (JP 5, BP 16 and UO 4), two of which were excluded via the established screening process such that 23 remain relevant (JP 4, BP 15, UO 4). Excluding cases of doubling for each subject, already identified in Step 3, 31 relevant reviews (JP 5, BP 19, UO 8) remain in the end, with Dakpo et al. (2016) appearing twice, namely for BP and UO.

3 Results of the literature search

According to the definition we stated in our introduction, all undesirable or bad outputs are byproducts and all byproducts are produced jointly with main products (goods as well as services). Thus, the number of sources that deal with these topics should regularly increase with the respective search terms from UO via BP to JP. However, as already mentioned in the first and second search step, the sources show only a few overlaps for the terms corresponding with the three subjects. The reason for this may be that the authors implicitly assume these connections but do

[8] For example, the paper by Hamilton (1996), cited over 200 times, deals with the topic of "Specification testing in Markow-switching time-series models". The author states in the abstract that "all of the tests can be constructed as a natural byproduct of the routine used to calculate the probability …". Another example (with most, i.e. more than 1,400 citations), which was also excluded, is a paper by Stuart et al. (1999), stating at the end of their abstract: "We also empirically demonstrate that much of the benefit of having prominent affiliates stems from the transfer of status that is an inherent byproduct of interorganizational associations.".

not explicitly express them (if the other two terms are known at all in the respective academic disciplines). But it may perhaps also reflect the fact that research on one of the three subjects hardly takes notice of the other two although they are strongly interconnected. Among other things, this will be examined in the following sections.

3.1 Relevant reviews

Table 1 contains the reviews—stated by authors, publication year, and number of citations—that were selected in the third and fourth search steps for the three subjects, with the single overlap between BP and UO mentioned above. Concerning JP and UO, all but one of the recorded reviews were published after 2015 whereas they accumulate from 2015 onwards regarding BP (with three earlier exceptions from 2002 and 2012). Reviews that do not address one or more of the five business, management, or economic categories used in Step 2, thus exclusively found in Step 4, are printed in SMALL CAPITALS in Table 1. Interestingly enough, and contrary to all UO reviews, almost all BP results were obtained in this way.

Table 1 Relevant reviews (with number of citations on Feb 22, 2022, within WoS Core Collection)

	Joint production (JP) (5 reviews)	Byproducts (BP) (19 reviews)	Undesirable outputs (UO) (8 reviews)
Until 2014			
		Desrochers (2002a): 49 RODEHUTSCORD ET AL. (2002):28 MURTY AND NAIDU (2012): 412	Chiu et al. (2011): 39
2015 – 2020			
	BUTTER-FIELD ET AL. (2016): 18 GARCIA ET AL. (2018): 6 BASKENT (2018): 6 Tah-vanainen et al. (2018): 5 Ovando and Brouwer (2019): 14	Walls and Paquin (2015): 82 CULIN AND MUSTAC (2015): 19 Dakpo et al. (2016): 133 LANFRANCHI ET AL. (2016): 20 Jain (2017): 0 DAHIYA AND NIGAM (2018): 3 CRAVOTTO ET AL. (2018): 23 Fidelis et al. (2019): 34 MAJERSKA ET AL. (2019): 50 PANWAR ET AL. (2019): 11 REZANIA ET AL. (2019):78 GARLAPATI ET AL. (2019): 20 CAMPOS ET AL. (2020): 50 BRANCA ET AL. (2020): 28 VILLACIS-CHIRIBOGA ET AL. (2020): 26 KHDAIR AND ABU-RUMMAN (2020):17	Dakpo et al. (2016): 133 Forsund (2018): 21 Halkos and Petrou (2019): 50 Wang et al. (2019): 27 Ma et al. (2019): 13 Otani and Yamada (2019): 2 Akbari et al. (2020): 7

Table 2 Most frequent research categories with their number of relevant reviews

Joint production (JP) (5 reviews)	Byproducts (BP) (19 reviews)	Undesirable outputs (UO) (8 reviews)
FORESTRY: 4	FOOD SCIENCE TECHNOLOGY: 4	Management: 4
Economics: 2	Management: 3	OR/MS: 4
	ENERGY FUELS: 3	Economics: 3
	Economics: 2	Business: 1
	BIOCHEMISTRY MOLECULAR BIOLOGY: 2	
	CHEMISTRY MULTIDISCIPLINARY: 2	
	Business: 1	
	OR/MS: 1	

Except for the categories used in Step 2 for refining the literature search, only those other categories (printed in SMALL CAPITALS) are listed for reasons of clarity which contain at least two reviews recorded by the WoS

Reviews regarding JP and BP regularly deal with specific application areas, identified in Table 2. It additionally shows the number of reviews assigned to the corresponding category (and possibly to others, too). It is striking that there are many reviews regarding the term BP which mainly deal with economic, business or management aspects, but are published in special journals of applied sciences which do not belong to the research areas Bus/Econ[9] and OR/MS. In contrast, all reviews featuring UO ("desire") as topic exclusively belong to these areas and categories. No review regarding JP is assigned to the categories 'OR/MS', 'Management', and 'Business', and none at all to 'Business Finance'.

An extensive content analysis of the reviews in question leads us to the important conclusion that there is no comprehensive review article on 'joint production' (JP) among the entire literature covered by the Web of Science, particularly none written from a general perspective of business, management, or economics.[10] Reviews on business and economic aspects of (harmless) 'byproducts' (BP) can be found almost only in the non-economic literature; quite frequently, they focus on application-specific aspects, whereby using the term 'byproduct' rather casually (nevertheless relatively often) and definitely not as part of any central concept. Reviews with 'undesirable' or 'bad output' (UO) as topic are less application-specific, but in general more methodically oriented.

[9] Even when referring to the Bus/Econ research area in our verbal argumentation, the statistical analyses are always based on its four categories, as this provides a more accurate picture.

[10] The historical review of Kurz (1986) is not listed within the WoS databases, as papers from *Metroeconomica* published before 2008 are not included. Further reviews that appeared in books are not captured either by WoS, e.g. Chapter 6 of Baumgärtner et al. (2006).

3.2 Characteristic features of the relevant literature

At this point, in addition to the reviews mentioned, all other papers which were found in the third search step and identified as relevant are also included in the further analysis to answer the research questions stated in the introduction.

3.2.1 Numerical development of literature and citations

Figure 2a–c show the development of the number of papers and citations recorded in the WoS Core Collection, each with respect to one of the three subjects. In view of the caveat mentioned in Sect. 2, which refers to the non-recording of abstracts and keywords by WoS before 1990, the figures regarding JP are even more remarkable for the period before 1990, especially when compared to BP and UO.

Concerning topic JP, approximately 25% of the papers found by the WoS were already published before 1990 (with more than 10% within the 1960s and 1970s), whereas almost all those papers on the topics BP and UO had not been published until the start of the 1990s (with six exceptions for BP and only one article by Pittman (1983) for UO). In terms of temporal distribution, a relatively steady level of publication activity can be seen for JP, with a slight increase from the 2000s onwards. In contrast, the number of papers increased moderately but significantly for BP and progressively for UO from 2005 onwards, particularly within the past decade.

Regarding the scientific perception of the papers found, the citations increased strongly within the past decade, not only for UO, but also for JP and BP. The average number of citations per item of the relevant papers considered here is about 31 regarding JP (with an h-index of 45 for the 254 considered papers), 30 for BP (h-index 42 for the 294 considered papers) and 44 for UO (h-index of 88 for the 674 considered papers).

3.2.2 Distribution within disciplines and journals

Tables 3 and 4 list in which research areas and in which journals the papers in question on our three subjects had been published most frequently (with non-economic areas marked by SMALL CAPITALS).

Because of the refinement within search Step 2 it is hardly surprising that WoS categories from the research areas Bus/Econ and OR/MS play important roles. All of our three subjects appear by far most frequently in the WoS category ‘Economics’, next or next but one followed by ‘OR/MS’, whereas ‘Management’ is at least an important category for BP and UO. Since each article is assigned to at least one of the five categories of Step 2, the sum of the five respective percentages should be equal to or greater than one (in

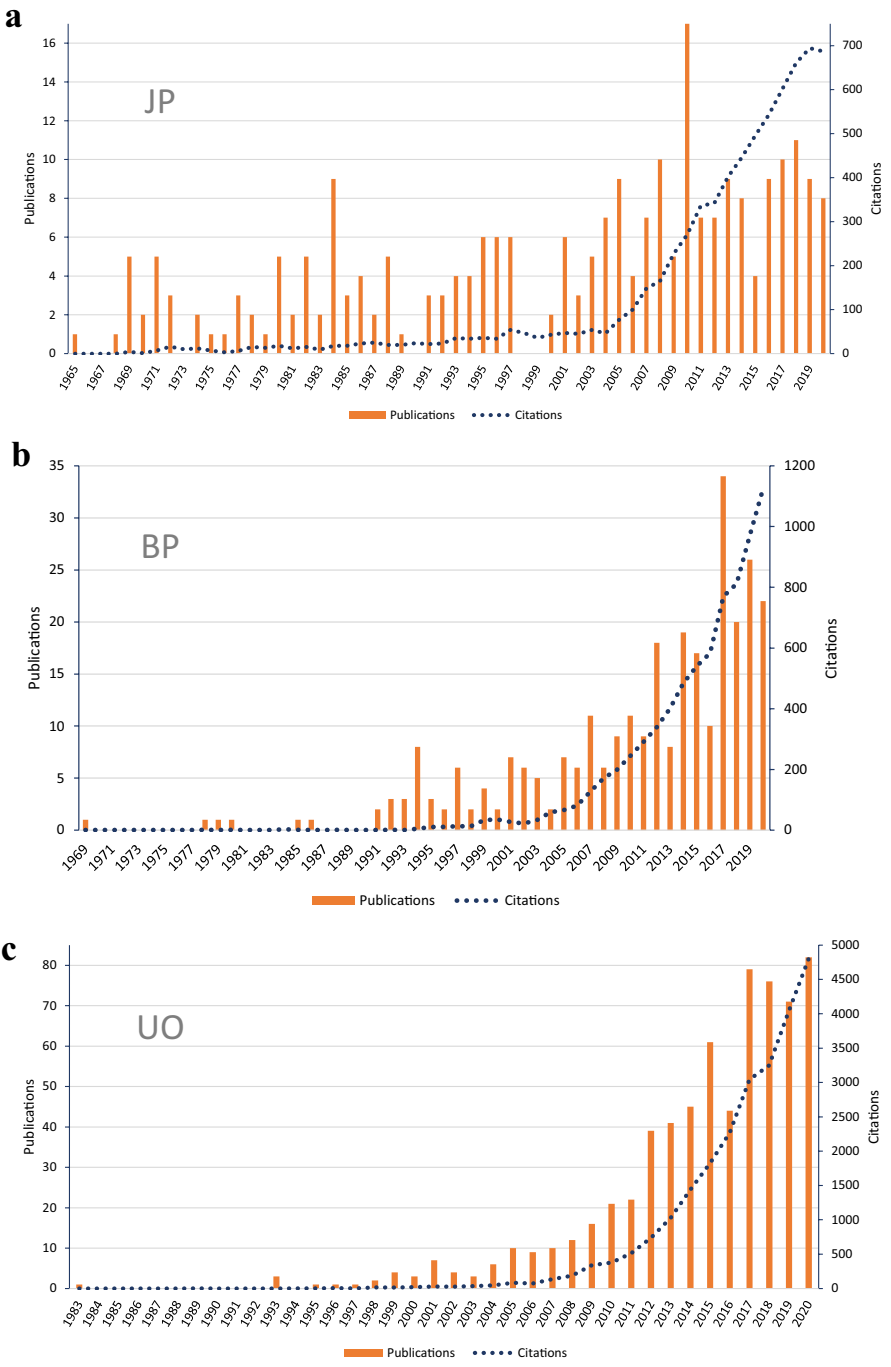

Fig. 2 Frequency of publications and citations regarding subject **a** 'joint production'. **b** 'byproduct', and **c** 'undesirable output'

Table 3 Research categories of the analysed papers with more than 3% of assignments

Joint production (JP) (254 publications)	Byproducts (BP) (294 publications)	Undesirable outputs (UO) (674 publications)
Economics: 84%	Economics: 59%	Economics: 59%
ENVIRONMENTAL STUDIES: 19%	OR/MS: 25%	OR/MS: 35%
OR/MS: 14%	ENVIRONMENTAL STUDIES: 24%	Management: 25%
MATH. METHODS IN SOCIAL SCIENCES: 11%	Management: 22%	ENVIRONMENTAL STUDIES: 18%
Business: 9%	ENVIRONMENTAL SCIENCES: 13%	ENVIRONMENTAL SCIENCES: 13%
ENVIRONMENTAL SCIENCES: 9%	Business: 12%	ENERGY FUELS: 10%
Management: 9%	ENERGY FUELS: 10%	Business: 8%
AGRICULTURAL ECONOMICS POLICY: 9%	AGRICULTURAL ECONOMICS POLICY: 9%	MATH. METHODS IN SOCIAL SCIENCES: 7%
Business Finance: 5%	INDUSTRIAL ENGINEERING: 7%	AGRICULTURAL ECONOMICS POLICY: 5%
ECOLOGY: 5%	MANUFACTURING ENGINEERING: 5%	TRANSPORTATION: 4%
ENERGY FUELS: 5%	MATH. METHODS IN SOCIAL SCIENCES: 4%	ECOLOGY: 4%
FORESTRY: 4%	FORESTRY: 3%	Business Finance: 3%
INDUSTRIAL ENGINEERING: 4%	ECOLOGY: 3%	MATHEMATICS (INTERDISCIPL. APPLICATIONS): 3%
MANUFACTURING ENGINEERING: 4%	Business Finance: 2%	TRANSPORTATION SCIENCE TECHNOLOGY: 3%
MATHEMATICS (INTERDISCIPL. APPLICATIONS): 4%		INDUSTRIAL ENGINEERING: 3%
TRANSPORTATION: 3%		
PROBABILITY STATISTICS: 3%		

Although only approximately 2% of BP papers are from the WoS category ‘Business Finance’ it is listed here because this category is one of the five WoS categories used for refinement in Step 2

Table 4 Journals in which more than 2% of the analysed papers are published

Joint production (JP) (254 publications)	Byproducts (BP) (294 publications)	Undesirable outputs (UO) (674 publications)
Ecological Economics: 4.7%	Energy Policy: 7.5%	Energy Economics: 10.5%
EJOR: 3.9%	EJOR: 5.1%	EJOR: 10.1%
Americ J Agricultural Econ: 3.5%	Ecological Economics: 3.1%	Energy Policy: 8.0%
Forest Policy and Econ: 3.5%	Environmental and Resource Economics: 2.7%	Annals OR: 5.9%
J Productivity Anal: 3.5%	Forest Policy and Economics: 2.7%	Omega Int J Man Sc: 3.9%
Energy Econ: 3.2%	Int J Prod Econ: 2.4%	Ecological Economics: 3.7%
J Political Econ: 3.2%	Energy Economics: 2.0%	J Productivity Analysis: 2.8%
Econometrica: 2.4%	Quality Access to Success: 2.0%	J OR Society: 2.7%
Energy Policy: 2.4%	Resource and Energy Economics: 2.0%	Environ. and Resource Economics: 2.4%
Environ Resource Econ: 2.4%		
J Banking Finance: 2.4%		
Resource and Energy Econ: 2.4%		

fact JP: 121%; BP: 120%; UO: 130%). Nearly 30% of the papers are assigned to more than one of these five categories,[11] however, if a paper belongs to several categories, the latter often do not have a direct link to business, management, or economic issues. Some of them, particularly from the research areas of environmental or energy sciences, display even more assignments than the two categories 'Business' and 'Business Finance', both of which together obtain 14% (for subjects JP and BP) at most. Thus, in comparison to the other three categories, relatively few papers of the two business categories are concerned with our search terms for joint production, byproducts, or undesirable outputs as topic.

With respect to Table 4, it is striking that the papers analysed by us are very much scattered over a wide range of diverse journals, mostly belonging to the research areas displayed in Table 3.[12] Economic journals as well as journals from environmental and energy sciences are the most popular publication titles for JP and even more for BP. Articles on UO seem to accumulate in certain OR/MS and energy journals. None of these articles with subject UO or subject BP appeared in one of the "top five"[13] economic journals, whereas 14 of the papers on subject JP listed in the WoS were published in the top five, beginning with the paper by Vinod (1968) and ending with that by Kotchen (2006) which, at the same time, is the last one of two since 1982.

3.2.3 Most frequently cited articles and prevalent authors

Tables 5 and 6 list the most frequently cited papers and the most prevalent authors for each of the three subjects, respectively. Table 5 shows that, excepting some papers on subjects JP and BP which are cited quite often, the papers on UO are more frequently cited, in general. As can be seen in Table 6, only few authors, especially Färe, Grosskopf, and Zhou, use all three search terms in their titles, abstracts, or keywords.

[11] A refined analysis shows that only 12 papers are assigned to three of these five WoS categories, namely for JP one to Econ, Man, OR/MS and one to OR/MS, Man, Bus; for BP one to Econ, OR/MS Man and two to Econ, Man, Bus; for UO seven, all to Econ, OR/MS, Man.

[12] Because the purpose of our paper is to analyse the literature of general and business economics, journals like e.g. *Journal of Cleaner Production* and *International Journal of LCA* are not considered. The Web of Science assigns these two journals exclusively to the research categories 'Engineering Environmental', 'Environmental Sciences', and 'Green Sustainable Science Technology', and not to any of the five categories of the research areas Bus/Econ and OR/MS. Thus, both journals do not occur in Table 4 because of the restriction in our search Step 2. Journals like e.g. *Forest Policy and Economics* are assigned to the categories 'Economics', 'Environmental Studies', and 'Forestry'. That is why such non-economic categories occur in Table 3.

[13] The "top five " are: *American Economic Review*, *Econometrica*, *Journal of Political Economy*, *Quarterly Journal of Economics*, and *Review of Economic Studies* (www.aeaweb.org/research/charts/publishing-promotion-economics-top-five).

Table 5 Most frequently cited papers (with citations on Feb 22, 2022, in WoS Core Collection)

Joint production (JP) (254 publications)	Byproducts (BP) (294 publications)	Undesirable outputs (UO) (674 publications)
Patterson (1996): 537	Linton et al. (2007): 860	Seiford and Zhu (2002): 846
Korhonen and Luptacik (2004): 392	Färe et al. (2005): 527	Färe et al. (2005): 527
Zhou and Ang (2008): 323	Connell (2006): 455	Scheel (2001): 489
Cornes and Sandler (1984): 282	Färe et al. (1993): 422	Färe et al. (1993): 422
Berger et al. (1993): 259	Andreoni and Levinson (2001): 380	Hailu and Veeman (2001): 397
Bagnoli and Watts (2003): 246	Zhou and Ang (2008): 323	Korhonen and Luptacik (2004): 392
Wu et al. (2012): 222	Spengler et al. (1997): 208	Färe and Grosskopf (2004): 367
Kotchen (2006): 180	Murty et al. (2012):184	Zhou et al. (2008): 336
Barnett and Masse (2007): 157	Zaim (2004): 170	Zhou et al. (2007): 325
Wang et al. (2012): 156	Park and Weber (2006): 140	Zhou and Ang (2008): 323
Wendland et al. (2010): 145	Dakpo et al. (2016): 133	Kuosmanen (2005): 283
Nalle et al. (2004): 128	Chertow et al. (2008): 126	Shi et al. (2010): 282
van den Berg and Spauwen (2006): 124	Mandal and Madheswaran (2010): 115	Kumar (2006): 274
Garcia and Thomas (2001): 121	Delmas and Lessem (2014): 93	Färe et al. (2004): 261
Cornes and Sandler (1994): 116	Riccardi et al. (2012): 93	Reinhard et al. (1999): 256
Mandal and Madheswaran (2010): 115	Yoruk and Zaim (2005): 93	Pittman (1983): 242
Pasurka (2006): 111	Reynaud (2003): 83	Färe et al. (1996): 230
Roels et al. (2010): 109	Walls and Paquin (2015): 82	Zhang and Choi (2013): 229
Kotchen (2005): 108	Cuesta et al. (2009): 79	Fukuyama and Weber (2010): 228
Managi et al. (2005): 107	Stindt and Sahamie (2014): 78	Zhang et al. (2013): 227

The UO paper by Färe et al. (1989), that we could not find through our systematic WoS search (cf. Section 2), is more frequently cited than any of the sources in Table 5 (1,088 times at Feb 22, 2022)

Table 6 Authors with most publications (and its respective number found by WoS)

Joint production (JP) (254 publications)	Byproducts (BP) (294 publications)	Undesirable outputs (UO) (674 publications)
Pasurka CA: 10	Dakpo KH: 6	Sueyoshi T: 31
Färe R: 9	Desrochers P: 6	Goto M: 24
Grosskopf S: 6	Arjomandi A: 4	Färe R: 18
Baumgärtner S: 4	Färe R: 4	Grosskopf S: 17
Kurz HD: 4	Grosskopf S: 4	Wu J: 16
Rodseth KL: 4	Lovell CAK: 4	Liang L: 14
Cornes R: 3	Murty S: 4	Managi S: 14
Dumenil G: 3	Rentz O: 4	Lozano S: 13
Fujimoto T: 3	Selvaggi R: 4	Zhou P: 13
Griffin JM: 3	Absi N: 3	Zhang N: 12
Kotchen MJ: 3	Kumar S: 3	Matousek R: 11
Levy D: 3	Managi S: 3	Pasurka CA: 11
Managi S: 3	Pappalardo G: 3	Song ML: 11
Sandler T: 3	Pecorino P: 3	Chiu YH: 10
Schefold B: 3	Zhou P: 3	Tsionas MG: 10
Seale JL: 3		Wang K: 10
Tsai WH: 3		Yu MM: 10
Zhou P: 3		

3.3 Main questions and issues dealt with

In order to obtain a more accurate impression of the contents of papers found by means of our four-step search approach, we went through the abstracts of all the papers. This content analysis revealed some findings, which were then complemented by additional search runs within the lists of results generated by Step 3 as well as a closer look at whole papers—particularly the reviews of Table 1—where it seemed useful.

It is evident that there is a very strong link between all of our three subjects and environmental issues. More than 35% of the JP papers and even 68% for BP and 72% for UO are concerned with topics that can be found by search strings *environm**, *ecolog** or *energ**, whereby the string *environm** accounts by far for the biggest share. Twelve of the papers deal with closed loop systems, as an additional analysis with the search strings *closed loop* and *reverse logist** shows (one paper for JP, none for UO and eleven for BP, including a review by Stindt and Sahamie (2014)[14]). Another cluster with twice as much papers that can be recognised, also almost exclusively regarding the subject BP (only one for JP), is characterised by the terms *industrial ecology* or *industrial symbiosis* (e.g. Desrochers (2002a), AlMassah (2018)). They describe the systematic use of (often undesired) byproducts within a network of companies. While industrial ecology has been a comprehensive research

[14] Although Stindt and Sahamie (2014) present a comprehensive review of research on closed loop supply chains in the process industry, it is not classified as such, but as a regular article in WoS and therefore it is not listed in Table 1.

field in environmental sciences from the late 1980s onwards, most of the papers found by our search (20 out of 24) appeared since 2010.[15]

Furthermore, the by-production technology approach (see e.g. Murty and Russell (2018)) is quite prominent in the literature we found, obviously in the majority of cases in connection with BP. It is proposed by Murty et al. (2012)—and further developed e.g. by Fang (2020)—in order to model pollution-generating technologies as the intersection of two sub-technologies: an intended-production one plus a residual-generation one. This approach has attracted quite some interest in the recent literature of performance measurement and therefore can also be found in the list of results concerning UO.[16]

Hence, a closer look at the UO papers reveals that they are usually concerned with the measurement of performance—mostly by data envelopment analysis (DEA)—to handle problems resulting from bad outputs. About 98% of the papers contain at least one of the search strings *effic**, *productiv**, *DEA* or *data envelop** as topic.[17] The majority of these papers deal with environment-related bad outputs (for strings *pollut**: 198, *waste**: 38, *CO2*: 133, *SO2*: 29, *NOx*: 18; several counted more than once). However, other kinds of undesired/bad outputs can also be found, particularly when service production processes are analysed. This applies foremost to the bank/financial sector with nearly 150 papers featuring the term as a topic,[18] as well as health issues (performance evaluation of hospitals, but also damages to health in the population due to environmental impacts). In these cases, risks of banking business or mortality rates are often considered as undesirable outputs. Other rather unusual (bad) outputs are dropouts at universities, customer complaints at hotels or missed shots of basketball teams.

Overall, the majority of performance measurement papers consider practical issues, particularly concerning UO. They often focus on companies, but they also have a look at sectors, regions, or entire countries, usually analysing specific cases without questioning the production-theoretical or technological foundations of the applied DEA model. However, there are exceptions which aim at the methodological development of DEA, particularly with respect to disposability assumptions (cf. the review by Dakpo et al. (2016)). In these papers, examples with real data are mainly used to illustrate methodological developments.

[15] A search in WoS Core Collection with the two search strings *industrial ecology* and *industrial symbiosis* leads to 3,113 papers, of which 267 also contain our search strings for JP, BP or UO. Whereas 179 of the 267 papers are assigned to the WoS category *Environmental Sciences*, 150 to *Environmental Engineering* and 146 to *Green Sustainability Science Technology*, only 24 are assigned to the OR/MS and Bus/Econ areas (OR/MS: 9; Econ: 7, Man: 12, Bus: 5, BusFin: 0; several counted twice).

[16] In contrast, the by-production approach has only been addressed by one JP paper (Ray et al. (2018)).

[17] Performance evaluation (derived by a specific search with the mentioned search strings) has also been considered to a remarkable extent in connection with the two other subjects, although altogether to a minor degree (32% for JP, 38% for BP).

[18] An additional search within the 674 UO papers with the strings *bank** and *financ** brought up 148 hits, which, however, also include some papers that are not suitable, e.g. three due to 'Banker' as author, who developed one of the basic DEA models.

The mentioned methodological contributions on performance measurement are complemented by other theoretical contributions dealing with the analysis of polluting technologies, the determination of pollution abatement costs or shadow prices of undesirable outputs. These were not only found through our search on the subject UO, but to a lesser extent also on the subjects JP and BP.[19] Concerning JP papers, they pursue a number of conceptual contributions to general economics that were written primarily in the last quarter of the past century. Nonetheless, a stronger orientation towards application-oriented issues, especially by the environmental, energy and agricultural sectors, is conceivable in the JP papers, as well as in the BP papers, since around the turn of the millennium.[20]

4 Discussion of the results

Our study revealed that a bulk of recent literature on joint production and its outputs addresses issues of performance measurement in cases of undesirable or 'bad' byproducts, primarily applying or further developing methods of data envelopment analysis (DEA). Important pioneering contributions are by Pittman (1983) followed by Färe et al. (1989, 1993). They showed how to adjust productivity calculations and efficiency measures, but also how to estimate output distance functions as frontiers in order to generate shadow values of the undesirable outputs that are required to make both types of adjustments. Next, we explain two kinds of categorical flaws existing in this literature on performance evaluation until today, before we turn to other shortcomings in the more general literature on joint production in the second subsection.

4.1 Category mistakes in the literature on performance measurement

DEA is a well-known methodology developed to measure the efficiency of similar decision-making units (DMUs) that transform multiple inputs into multiple outputs. Thousands of DEA applications have been published in the scientific literature (Liu et al. 2013a, b; Lampe and Hilgers 2015). Taking ecological or environmental objectives into account by incorporating bads as outputs has been one of the main strands of development of efficiency measurement in the past two decades. However, as a

[19] 17% of the papers found for UO as well as 7% each for JP and for BP also included the terms *pollution abatement* or *shadow price** as topic.

[20] Reviews by Tahvanainen et al. (2018) on synergies in the joint production of timber and mushrooms, or—more general—by Butterfield et al. (2016) on the tradeoffs and compatibilities of multiple functions among ecosystem services are examples here.

rule, DEA assumes that outputs are to be maximised and inputs to be minimised. Thus, the problem arises how to deal with undesirable outputs.[21]

4.1.1 The problem of data envelopment analysis with undesirable outputs

There is an intense, still ongoing debate about how to cope with pollutants in DEA (cf. footnote 3), which is also reflected in the corresponding literature found by us. In their review, Dakpo et al. (2016, p. 357) emphasise the fact that "[c]onsidering pollutants as inputs is not a correct way of modelling pollution-generating technologies." In contrast, Halkos and Petrou (2019, p. 102) suggest to consider bad outputs as DEA 'inputs' as one of four possible options that each "has its benefits and drawbacks which each researcher should take into account at every stage of their research and assess which method is more appropriate to be used." They conclude their review with the assertion that incorporating undesirable outputs has proven to be quite a challenge for DEA researchers.

In our view, the essential reason for this seemingly still unmastered challenge is that the literature on efficiency measurement with bads as inputs or outputs widely ignores the specific nature of this challenge. It requires a theoretical foundation that must be based on an integration of both production theory and multicriteria decision analysis. This neglect results, among other things, in category mistakes concerning the use of the terms 'input' and 'output' in certain parts of the economic and performance measurement literature. In fact, the challenge stated above by Halkos and Petrou (2019) can be mastered in principle if the following guideline is observed.[22]

4.1.2 Distinguish inputs and outputs categorically from outcomes and values!

Figure 3 outlines the basic structure of production-based performance evaluation methods as generic guideline for a recursive process with four strongly interdependent steps or components, which is similar to the process of life cycle assessment (LCA) as defined in ISO 14040 (Dyckhoff and Souren 2022): In the fundamental first step, the evaluation's subject and objectives as well as the decision field with its alternatives of how to execute the process to be assessed will be specified; this includes the goal and main purposes of a performance assessment as well as the determination of the relevant types of inputs and outputs combined with those types of resulting outcomes that are relevant impacts on certain economic, social or ecological environments. In the second step, the input and output quantities which influence the selected objectives via the impacts are determined. Based on that, all relevant outcomes are assessed in the third step and then valued by one or more performance measures in the fourth step. Usually, the decision-maker or an external evaluator is responsible for the interpretation of the results in each step.

It is essential to note that output and outcome are not of the same conceptual categories! By definition, *input* enters into and *output* emerges out of the transformation process (Frisch

[21] An opposite problem of similar nature exists for some input factors such as waste to be disposed of (cf. Wojcik et al. (2017)), but in a certain sense also for 'dual-role factors', such as third-party funds acquired for the employment of research staff of universities (Fandel 2007).

[22] As an example, see Sect. 5.3.2 of Dyckhoff and Souren (2022).

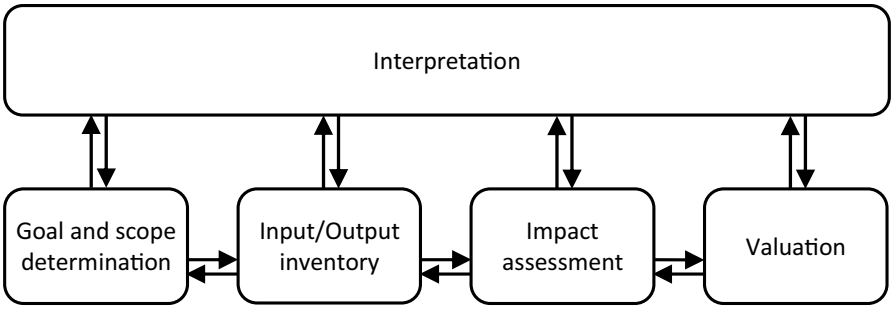

Fig. 3 Generic structure of production-based performance evaluation (cf. Dyckhoff and Souren (2022, p. 799))

1965, p. 3). They form flows (measured in time rates) that are directly linked to an execution of the process and are regularly identified with it. In contrast, an *outcome* of the process is defined here as consequence, effect, or impact for a particular environment that is caused by the process indirectly (mostly via the inputs and outputs). For example, carbon dioxide emissions are byproducts of the main product power if produced by burning fossil fuels, whereas the pollution of (and immission into) the atmosphere by these emissions, with its impact on Earth's climate, is an outcome—called 'external effect' in economics. Because this effect is valued negatively (step 4 of Fig. 3)—and consequently called 'external costs'—, carbon dioxide emissions are undesirable outputs. On the other hand, inputs may imply outcomes, too. For example, labour (as a 'good' service to execute the production process) is supposed to be used sparingly from the employer's point of view because the wage to be paid for the employed labour is an outcome that reduces their financial assets so that labour input is undesirable for them (but unavoidable). On the contrary, the input of garbage (as 'bad' things) into a waste incineration plant is desirable for the public because it reduces its (potentially harmful) stock as intended outcome (cf. Wojcik et al. (2017)).

Whereas the equalisation of the terms 'outcome' (in the sense of impact) and 'output' confuses two different conceptual categories[23] in that it intermingles both middle steps of the generic structure of Fig. 3, a second kind of category mistake is made by mixing the second and fourth step of performance evaluation without distinguishing these two components of performance evaluation *conceptually*, namely when inputs as well as outputs are used as synonyms for values.[24] This mistake is often made when applying DEA methods to non-production contexts (Dyckhoff and Souren 2022). A quote of Cook et al. (2014, p. 2) from their methodological review makes it quite clear:

> If [..] the DEA problem is a general benchmarking problem, then the inputs are usually the 'less-the-better' type of performance measures and the outputs […]

[23] To avoid such a confusion we propose to use the terms 'impact', 'effect', or 'consequence' instead of 'outcome'.

[24] When the quantities of inputs are minimised and those of outputs maximised, e.g. in DEA and economics, they form 'proxies' for the values of the actual goals, which are otherwise difficult to measure. Then, these proxies simultaneously represent both (objective) physical quantities and (subjective) values.

> the 'more the-better' type […]. DEA then can be viewed as a multiple-criteria evaluation methodology where […] the DEA inputs and outputs are two sets of performance criteria where one set (inputs) is to be minimized and the other (outputs) to be maximized.

Such confusions can be avoided in principle by a sharp distinction between three different categories of notions affected by the production process to be evaluated: (1) the inputs and outputs, mostly determined technologically and easy to observe; (2) the results (consequences, effects, impacts, or outcomes) for the human, social, economic, or natural environments of the production system, mainly influenced by the observed inputs and outputs in an objectively or intersubjectively measurable manner; and (3) the costs and benefits as—often subjective, non-financial, incommensurable—values destroyed or created by the process via its results, evaluated with respect to the preferences of a certain person or authority. Such a strict distinction between important notions facilitates to use the knowledge of different academic disciplines as well as of practical experience of the application areas concerned—and hopefully contributes to avoid category mistakes (cf. Dyckhoff and Souren (2022) for a more elaborate explanation).

A category mistake may imply invalid empirical results because the inputs and outputs of production processes are confused with resulting impacts destroying or creating values (to be minimised or maximised, respectively). This illustrates a fundamental conflict caused by ignoring the necessary integration of both the production and the multicriteria perspective of a production-based performance evaluation.[25] Moreover, from a pure multicriteria perspective, as in the above quote of Cook et al. (2014, p. 2), a production theoretical foundation is lacking. In this case, there is no justification to envelop the measured 'input' and 'output' data of the considered DMUs in DEA by using assumptions like convexity or certain economies of scale in order to establish a set of additional production activities which are fictional but would nevertheless be (technologically) possible. Dyckhoff and Souren (2022) demonstrate and explain this fundamental flaw of many DEA applications by a simple graphical example.

4.2 Shortcomings in the general literature on joint production

Terminological deficits and fuzzy concepts—in this context concerned with different manifestations of joint outputs emerging from various types of processes—may imply that widely accepted models do not have sufficient external validity when applied in real life.

[25] Caballero et al. (2016, p. 2) wrote in their introduction to a special journal volume on linking economics to multiple criteria decision making (MCDM): "[T]he acceptability of a theory requires not only its internal coherence, but also a good level of external coherence or correspondence to the factual reality (i.e., a certain degree of empirical corroboration). … In short, MCDM remains somewhat unknown in what can be considered orthodox economics. But it would seem to be totally acceptable that if economic problems would be underpinned by the MCDM optimization theory instead of the classic one, at least some of the lack of external coherence problems pointed out above would be considerably mitigated.".

4.2.1 Relevance of important terms of joint production in the recent literature

Although Sect. 3 has shown that *undesirable* (or *bad*) *output* is a well-known and established technical term in the literature, the term does not appear in the title or abstract nor as a keyword chosen by the authors themselves in about one third of the papers that can be found by the Web of Science on this topic. In these cases, it is merely mentioned as a 'keyword plus' added by the Web of Science. Instead of 'undesirable' or 'bad' output, such papers use other terms, e.g. 'pollutant' and 'waste', or name concrete physical objects like SO_2 and CO_2. Furthermore, there are also publications on similar subjects that do not use any of these terms in their title, abstract, or as keyword—and thus were not found by our search strings—, but deal with an environmental, ecological or other topic which is concerned with bad outputs, too.[26] However, to our knowledge, the collection of sources found in Sect. 2 seems to be representative so that the results and conclusions of our paper should nonetheless be valid in principle.[27]

In contrast, *byproduct* does not seem to be a technical term in the business and economic literature. While the terms 'byproduct' and 'by-product(ion)'—but even more the common text strings 'by product(ion)'—are very often used in the abstracts of papers (as explained in Sect. 2), it very rarely appears in the title (cf. footnote 6) or as a keyword (-plus). Most of the 294 publications found in Sect. 2 use the term to characterise a bad byproduct, sometimes together with the term 'undesirable output'.[28] Notwithstanding this practice, a still small, yet recently increasing stream of publications considers byproducts which may have or get a positive price or value.[29] They are often concerned with industrial ecology or closed loop supply chain management (cf. Section 3.3). An early paper is by the historian Pierre Desrochers (2002a, p. 1031) who determines a main goal of industrial ecology "to find ways to make modern industrial economies mimic ecosystems by transforming the waste of one firm into the valuable input of another." Such an 'industrial symbiosis', sometimes also called "by-product synergy" (cf. Zhu et al. (2021)), is not a break with past practices, but rather a widespread phenomenon that has been neglected by contemporary researchers (Desrochers 2002b). Converting a waste stream into a useful and saleable byproduct may create an operational synergy between two jointly produced outputs. It can lead to counterintuitive profit-maximising strategies such as increasing the amount of waste generated, and thus increasing the quantity of original product above the business-as-usual production volume (Lee 2012).

With these exceptions, our literature study confirms, nonetheless, that byproducts, particularly harmless ones, are largely neglected by the academic research focused on

[26] An example is the frequently cited paper by Dyckhoff and Allen (2001).

[27] Similar caveats hold for the search strings of the other two subjects. This underlines the fact that there aren't any largely accepted terms and notions which are used as standards for the important phenomena discussed in our paper.

[28] E.g. the frequently cited papers of Färe et al. (1993) and (2005) as well as a recent paper of Ray et al. (2018).

[29] E.g. He and Lee (2016), Lee and Tongarlak (2017), Sun et al. (2017), Vanzetti et al. (2017), Yerushalmi (2018), Zhou et al. (2020).

business, management, and economics, although this phenomenon plays a non-negligible role in many economic sectors, particularly in agriculture and forestry or in the chemical and energy-producing industries. Byproducts such as tannic acid and sulphuric acid were initially disposed of in nearby rivers by the new textile industries of the nineteenth century in England. They later became undesirable (outputs) due to governmental regulations prohibiting this kind of harmful disposal. In the course of technical progress and due to innovations, sulphuric acid is now an intermediate product of paramount economic importance in the chemical industry. Whether an output is desired or undesired, is not predefined per se, but depends on the economic circumstances which change over time (Kronenberg and Winkler 2009).

Despite the long tradition of *joint production* in the economic literature, the respective technical term is no longer used with adequate frequency, as our study shows. This is surprising given the extensive literature on undesirable outputs (found in our study), as these emerge from joint production. In fact, bad byproducts usually arise with a specific manifestation of joint production. Although representing ubiquitous phenomena in real life, there isn't any unique, unambiguous term for it in the English-language literature. In the German-language business economics literature, it is referred to as 'coupled production', and sometimes also as 'primarily joint production'.[30]

4.2.2 Every production is coupled production, isn't it?

Any output of a transformation process is a *coupled output* of a different output if it necessarily emerges from the process together with the other output. Such a process, which must inevitably produce at least two different kinds of outputs that are recognised as such by the producer, model builder or evaluator, is called 'coupled production in the broadest sense' (Dyckhoff 1994, p. 13f).

From a scientific point of view, production is always coupled production. According to the Second Law of Thermodynamics (Entropy Law), every process is connected with a transformation of energy in such a way that the quality of the energy to do work always decreases or the entropy increases as a measure of the "disorder" or energy that is not capable of doing work (Romer 1976, p. 255):

> The second law of thermodynamics states that in every process, there is a universal tendency toward increasing disorder, increasing entropy, a degradation of energy. In a *closed* system, entropy can at best remain constant; in almost every process, the total entropy of all the things involved increases to some extent, and it never decreases. As time goes on, the entropy tends to increase, and this serves to distinguish the future from the past. This is not to say that the entropy, the disorder, of *part* of the system cannot decrease, but that any local decrease of entropy must be compensated for by at least an equal increase somewhere else.

[30] For more than hundred years (Schmalenbach 1919), the German term for this type has been "gekoppelte Produktion" or "Kuppelproduktion", but also "primär verbundene Produktion" (Riebel 1996).

Accordingly, energy of lower quality is an unavoidable output of any process, and thus of any good or service to be produced. Baumgärtner et al. (2006) based their ground-breaking analysis on this thermodynamic view. Their book is essential for anyone concerned with the (ecological) economics of coupled production. Yet, it seems that little attention has been paid to it in the relevant literature until now.[31] It is a pity that the authors use the traditional term 'joint production' for this kind of production,[32] although they are aware of the fuzzy, ambiguous, or even inconsistent contents that many users associate with this term (p. 17): "There is a huge number of classifications and terms referring to different types of multi-output production. Most of them are not compatible with each other, and one and the same term is used by different classification schemes to denote very different production patterns." Therefore, we propose a basic terminology that is largely compatible with most of the existing literature and at the same time allows researchers to be aware of possible pitfalls in using these or other terms.[33]

Since, from a thermodynamic point of view, every production is coupled production (Georgescu-Roegen 1971), the latter notion would be superfluous as the term 'production' would suffice. Nevertheless, as most of all byproducts, including entropy, are not considered in economic studies – not even in usual ecological ones, too –, the above defined term *coupled production* ("in the broadest sense") makes sense *from a practical point of view* if it is restricted to the specific choice of those outputs that are actually taken into account. Frisch (1965, p. 14) concluded with respect to the countless number of objects which are part of a production process or influence it: "No analysis, however completely it is carried out, can include all these things at once. In undertaking a production analysis we must therefore select certain factors whose effect we wish to consider more closely." One can call this a *representation* of the process or corresponding system (Baumgärtner et al. (2006), p. 29).

General economics as well as business economics regard *production* usually as value creation, i.e., as process directed and controlled by human beings which transforms (input into output) objects with the intention of generating advantages that outweigh the disadvantages of the transformation. Therefore, any economic production theory must be decision-based such that it takes the perceptions, intentions, and preferences of the producers into consideration, i.e., of the human beings directing and controlling the production process. Therefore, it isn't merely a question of how to model a production system on the bases of pure technological production possibilities. In fact, it is also the question of how to decide whether an output is a main product or a byproduct and whether it is desirable or undesirable, or even not

[31] According to Google Scholar, this book had been cited less than 100 times until 2021.

[32] Dakpo and Ang (2019, p. 604) mistakenly remark that "Baumgärtner et al. (2001) used the term of 'joint production' to describe economic systems that simultaneously produce desirable and undesirable goods." In fact, 'simultaneously' means something different from 'necessarily' or 'inevitably'. This is a further example of many imprecise usages of terms and notions in the reviewed literature.

[33] Formal definitions and more detailed reasoning are given by Baumgärtner et al. (2006). Besides the different term used by them ('joint' instead of 'coupled' production), their conception and ours are mainly distinguished by the fact that they do not suppose a purpose for production systems so that they also include pure natural systems outside of the economy into their analysis.

considered at all, or whether two different outputs are categorised as of the same quality (type) or not (Dyckhoff 1994).[34]

In our introduction, we defined a main product as a type of (desirable) output, for whose production (in certain quantities) the process has been established and is performed, such that it determines a *purpose* of the process or corresponding production system. The purpose of a process may also comprise the disposing of certain bads in such a way that they form the *intended input* of so-called 'destruction' or *reduction* processes (Souren 1996), e.g., the abatement of a stock of garbage by burning it in waste incineration plants or the disassembly of end-of-life vehicles, old buildings or nuclear power plants. As a rule, because of physical laws of mass and energy balances, such reductions result in a lot of different new types of coupled outputs often being undesirable too.

Thus, from an *economic point of view*, coupled production merely refers to those processes where a considered output unavoidably emerges from the process (in serving a purpose) such that this output, taken account of, differs from and is coupled with at least one intended (good) output or (bad) input. In particular, coupled production *in a narrow sense* is defined as special type of those instances in which at least one coupled output is intended itself, and then called *coproduct*,[35] i.e., when a main product inevitably emerges from fulfilling another purpose of the represented process or system (Dyckhoff 1994, p. 14).

The above notions of coupled production are relative as they depend on the specification of three principal aspects of the considered production system (Dyckhoff 1996):

1. its characteristics, in particular its technology and boundaries
2. its representation, in particular the specification of the considered outputs, and
3. its purposes.

Lignite combustion with the purpose of generating electricity provides an example of all three aspects. When, in the first step of power generation, sulphurous lignite is combusted, sulphur dioxide (SO_2) is a coupled output of the heat produced. The emission of SO_2 can be avoided by adding a filtering process to the production system. Consequently, flue-gas desulphurisation gypsum emerges as a new coupled byproduct. Its value is ambiguous, i.e., either positive or negative depending on the

[34] A byproduct is often rather indistinguishable from a main product concerning quality, so it may be difficult to formally rigorously define products with purpose from those without. An external observer does not easily recognise the purpose of a production process with several outputs. However, this also applies to the distinction of desired or undesired outputs by the producers if there are no objective criteria such as market prices. Econometric tests by Jordan (2017) show that price responses are not readily explained by the classification of metals as a byproduct or a main product based on revenue.

[35] The term 'coproduct' (or 'co-product') forms a topic in more than 5,000 publications of the WoS Core Collection until 2020, mostly belonging to Energy, Environmental and Food Sciences, Chemistry, Biotechnology as well as Mathematics. Only about 50 entries belong to the categories of Bus/Econ or OR/MS defined in Sect. 2, e.g. the paper of Chen et al. (2017). As a rule, the term is not clearly defined in this literature, and it is often used in the sense of 'useful byproduct', seldom as defined above.

actual local market conditions. For a long time, however, power plants served as prime examples of single(-product) production in economic textbooks, because all byproducts were regarded as economically irrelevant. Yet nowadays, coupled outputs such as greenhouse gas emissions can no longer be ignored. Moreover, the unavoidable residual heat from combustion is often utilised as second main product, in this way forming a purpose of its own so that this 'combined heat and power plant' represents coupled production in the narrow sense.

4.3 Coupled production and related phenomena in general economic theory

Problems of joint production played a significant role in the evolution of economic thought during the nineteenth century. This is a main conclusion of Kurz's (1986) historical investigation, already stated in our introduction. Baumgärtner (2000) carried forward this analysis into the twentieth century. Do the results of our literature study confirm Baumgärtner's findings for the first two decades of the twenty-first century, too?

Based on his findings, the detailed Chapter 6 on "Joint Production in the History of Economic Thought" by Baumgärtner et al. (2006) assesses a substantial body of both theory and applications of joint production in the literature—of general as well as of business economics—, stressing that the case of all joint outputs as desired goods has received most treatment (p. 6). Nevertheless, Baumgärtner et al. (2006, p. 143) conclude that the prevailing economic theory has serious gaps regarding joint production. They attribute this to the dominant research strategy of economics in the twentieth century when, "under the influence of the structuralist paradigm, theorem-oriented theorising has taken over from problem-oriented theorising in guiding the further development of economic theory" (p. 156). Although economic thinking has produced many interesting, relevant, and applicable results concerning the existence, efficiency, and other properties of the economic equilibrium in different settings of joint production, they found two major gaps in the economics of joint production at the turn of the millennium (Baumgärtner et al. (2006, p. 142)):

> 1. There are satisfying explanations for both (i) joint production of several desired goods (in the general competitive equilibrium theory à la Arrow-Debreu and in the partial equilibrium theory of industrial organisation) and (ii) joint production of desired goods and harmful bads (in the welfare theory of externalities). But both of these approaches presuppose an a priori knowledge of the character of outputs, i.e. whether they are positively or negatively valued, instead of determining it endogenously from the analysis. In the former approach, the positive character of the outputs is artificially imposed, e.g. by assuming free disposal in general equilibrium analysis or by limiting the analysis to solely the marketable outputs of a firm in industrial organisation; in the latter approach the negative character goes into the theory as a basic assumption. What we lack is a general and encompassing theory of joint production that does not simply assume, or impose, the character of the outputs as positively or negatively valued, but endogenously derives this character.

> 2. In the case of harmful pollutants causing public negative externalities—a case that is characteristic for some of the most pressing environmental problems of our time and therefore is of utmost importance for environmental policy—economics essentially leaves us without any operational result: while there are solutions […] that work in theory, it is also clear that they will not work in practice due to incentive incompatibility.

Baumgärtner et al. (2006) address both these gaps in their book. Although they define the term 'joint production' similarly to our stricter notion of coupled production, i.e., it "denotes the phenomenon that several outputs necessarily emerge from economic activity" (p. 2), they make no clear distinction between the different types of joint production, particularly not in their historical chapter. For example, both from the neoclassical as well as from the neo-Ricardian point of view, the existence of a general equilibrium in a competitive economy is based on the standard assumption of free disposal so that undesirable and harmful joint outputs can be disposed of at no costs. However, a production system that includes activities which allow to dispose of each joint output, even at some costs, does not fulfil the definition of coupled production! Nonetheless, the subsystem from which the joint outputs originally emerged—i.e., the production system without additional 'end-of-pipe' disposal activities—may consist completely of processes of coupled production itself.

To cope with undesirable outputs inevitably emerging with intended outputs from coupled production, Shephard (1970, p. 187) introduced the technological assumption of 'weak disposability' such that the undesirable outputs can be reduced only by a proportionate decrease of the desirable outputs. Despite several limitations, e.g. free disposability of inputs, this assumption is still the most widely used approach for benchmarking under the conditions of a pollution-generating technology (Dakpo and Ang 2019, p. 615), although various alternative disposability assumptions were proposed and used in applications in the past two decades. They are reviewed and criticised by Dakpo et al. (2016) and Dakpo and Ang (2019) who are in favour of structural representations with multiple equations. Dakpo and Ang (2019, p. 640) remark that the by-production approach (cf. Sect. 3.3) "is typical for engineering science and is appealing for economists. [It] opens the black box by making the technical relationships between all inputs and outputs explicit. This increase in accuracy does, however, require appropriate knowledge of the production system …" In our view, disposability assumptions cannot be generic at all, but should be carefully justified by technological reasons relating to the physical production process in question (Dyckhoff 2019). To this end, the designer of the production model needs to have a deep understanding of all affected spheres of reality. Therefore, we agree with Rodseth (2014, p. 211) "that the popular production models that incorporate undesirable outputs may not be applicable to all cases involving pollution production and that more emphasis on appropriate empirical specifications is needed."

Summing up, our literature study largely confirms the above cited assertions of Baumgärtner et al. (2006) for the past century as far as the entries of the Web of Science are concerned, whereas in the first two decades of the current century, the literature on multi-output production with at least one undesirable output increased strongly. However, such articles are mostly concerned with the measurement of

efficiency and productivity and were published in specialised journals on methodical issues or applied areas such as e.g. agricultural, energy, ecological or empirical economics.

There is only a single article in one of the 'top five' economic journals (cf. Sect. 3.2.2) of the past three decades which used the historically important term 'joint production', namely that of Kotchen (2006) on the "joint production of a private good and an environmental public good". Hence, our literature study seems to confirm the overall assessment that Baumgärtner et al. (2006, p. 139) already stated for the state-of-the-art at the end of the past century: "Today, the analysis of joint production as an explicit issue is—with few exceptions—not on the agenda of economics anymore. While various economic theories capture special dimensions of joint production, there exists no encompassing and general theory of joint production."

4.4 Coupled production and related phenomena in business economic theory

Kurz (1986, p. 2), while also criticising the lack of attention paid to joint production by (general) economics, notes: "Apparently, business economists were generally much better aware of the importance of joint production than most other economists; see, for example, Riebel (1955)." Riebel himself payed tribute to the German business management literature of the first half of the twentieth century by summing up critically (pp. 19–20; own translation):

> From this rough overview of the most important questions […] it can be seen that one has essentially restricted oneself to examining coupled production unilaterally regarding the aspect of pricing and valuation as well as the handling of technical accounting, without sufficiently going into depth. The reasons for this are, on the one hand, the question areas that have been in the foreground up to now […] and, on the other hand, the time- and problem-related selection of certain parts of the 'object of experience'. Whereas at the beginning of modern business science, the focus was on commercial enterprises and later on banks, these sub-areas of the research object 'economy' were more and more replaced by industrial enterprises, namely of the type of mechanical-technological branches of the assembly (machine, vehicle industry) and occasionally of the iron-working industry. […]
> Those branches of industry in which the phenomenon of coupled production is most prevalent from an economic and technical point of view, such as agricultural and mining production, the processing industries, and especially the chemical-technological industries in the broadest sense, have been dealt with in greater or lesser detail in numerous monographs, but have not been able to replace the machine-building industry from its position as the "standard example of business science" (both general and industrial). […] Even the ironworks which are relatively often used as an object of experience, e.g. blast furnace operations, still focus on economic and technical concerns to such an extent on the intended product, iron, that most authors are not fully aware of the special problems of coupled production.

Riebel's (1955) own pioneering work on coupled production is full of concrete examples taken from economic practice. He draws following main conclusion (pp. 225–226; own translation):

> [T]he decisive economic problem arises from the tensions between the special constraining conditions of production and the quite different conditions of demand. The degree of these tensions increases, on the one hand, with the rigidity of production and, on the other hand, with the degree of ties to demand. There are fundamental differences between the synthetic processes on the one hand and the analytical and exchange processes on the other hand. A virtually opposite economic school of thought permeates most of the business management issues of these types. This contrast is particularly evident with regard to the striving for economic efficiency and the technical-economic development, which, in the case of the synthetic processes, are organised towards loss-free and ballast-free single-product operation, while the other group strives for optimal material utilisation. The ever-increasing splitting of raw materials, the growing number of successive splitting stages, the connection of further processing plants, systematic research concerning intended uses with a higher beneficial effect are the visible signs of this development.

A critical view, similar to that of German business literature on coupled production, can also be found with respect to the international literature at that time (Dano 1966, p. 166f):

> In view of the fact that multiple production appears to be the rule rather than the exception, it may well be said that single-output models have been given rather more than due attention in the literature. […] However, some justification of the predominance of single-output models in the theory of production may be sought in the fact that it is often possible to decompose a multi-product model into separate models for the respective products, […] [S]uch cases will be treated as *alternative processes* and only the non-decomposable models will be referred to as cases of truly *joint production* …

'Truly joint' products are not necessarily unavoidable but may be produced together to make better use of scarce resources or to benefit from other synergies. For example, bread and cakes may be baked separately one after the other in one oven, but also together in order to use the free capacity of the oven.[36] Dano (1966, p. 167) adds a footnote: "This fundamental distinction will usually but not always coincide with the criterion whether or not it is possible (though not necessarily economical) to produce each output without making any of the others. Limiting cases

[36] In this case of truly joint production, the two-product process is not additively separable into two independent processes, contrary to *alternative* production that forms a sort of usually additively separable joint production. In contrast, production systems with separate processes, i.e. without any production interdependencies (except potentially for management capacities), are characterised as non-joint and called *parallel* production.

are conceivable where solutions on the boundary of the range of product substitution are possible even though the joint process cannot be decomposed."

If a certain restricted substitution between main products is possible, such a *coupling* is called *flexible* or *elastic* to some extent (Dyckhoff 1994, p. 107); otherwise the coupling is *fixed*, *complete* or *rigid*, i.e. the products are complementary and form a 'product bundle' (von Stackelberg, 1932). However, products are not coupled at all if total substitution between them is possible. Such an *alternative* production, as limiting case of extremely flexible coupled production, forms the second type of *rival* production, i.e. with main products competing for (efficient) production possibilities.[37]

Figure 4 illustrates these different types by showing the quantities of two products that can be produced with a given capacity of available input quantities. Analogous types can also be defined for all other kinds of compensative relationships between desirable and undesirable outputs (Dyckhoff 1994, p. 101ff).

Moreover, real life production systems demonstrate that each of these multi-output production types exists in various manifestations.[38] Numerous mathematical models and methods have been developed in OR/MS to deal with corresponding planning, scheduling, and accounting problems. For example, linear programming models have been used for oil refining on a regular basis since the 1950s. Today, the application of OR/MS methods is common practice in all larger companies of industries that are heavily affected by coupled production, such as the chemical or iron and steel industries.[39] This is reflected in a wealth of publications, mostly in OR/MS journals or those of operations planning and production management.[40] However, the term 'joint product(ion)' is usually not addressed as such.[41]

Thus, dealing with planning, scheduling, and accounting problems of joint production, particularly of coupled production, has been a standard industrial practice since the middle of the twentieth century (Kilger 1973, p. 365f). This is in stark contrast to the long neglect of coupled production in business economics' theory, as Dyckhoff (2022) concludes from his historical investigation (cf. also Schneider (1997), p. 336). It was only in response to the increasing environmental problems

[37] Ragnar Frisch (1965) is one of the rare exceptions of authors in the English-language literature who developed a more detailed distinction of the production of multiple (main) products, which is in parts like ours (but not identical). He uses the terms 'assorted' for a special type of alternative production. Furthermore, he defined a "degree of coupling" of products. However, his definitions are only concerned with main products and not with undesirable outputs. Moreover, he uses the concept of production functions, and not that of efficient production, as usual at his time.

[38] For a typology of elementary and complex processes of coupled (and other kinds of joint) production see Dyckhoff (1994), particularly Dyckhoff et al. (1997).

[39] One of the authors was previously concerned with cutting stock problems (Dyckhoff 1981), also called trim loss problems, which are essential for a variety of industries (cf. Dyckhoff et al. (1985)). He developed an approach for a specific production theory of cutting stock and trim loss processes (Dyckhoff 1988).

[40] Corresponding optimisation models can also be found in general business journals. For example, the *Journal of Business Economics* has often (implicitly) addressed practical issues of coupled production, most recently see e.g. Scheller et al. (2021) and Thies et al. (2021); cf. also the editorials of issues 9/2020 and 2/2021 by Fandel et al. (2020) and (2021).

[41] For this reason, we did not find these and similar sources in our literature search in Sect. 2.

and their reverberations, both in the public's mind and in business practice, that German business economists took up the topic of scarce resources and harmful emissions in the last quarter of the twentieth century, particularly from the mid-1980s to the mid-1990s and thereafter only in certain specialised research fields like production economics or sustainability management.[42] However, precise definitions of coupled and other types of joint production are still not established as a standard until today (Dyckhoff 2022). The present study proves that this is true for business-related journals of the international literature, too. Section 3.2.2 reveals that the respective number of papers using the terms of 'joint production' is small and not growing.[43]

5 Conclusions

Summing up, the results of our literature study are in several ways ambivalent. On the one hand, it is obvious that, after decades of neglect, the analysis of undesirable outputs has arrived in specialised disciplines of economics since the last quarter of the twentieth century and has even strongly increased in the past two decades. On the other hand, in addition to harmful byproducts, there are also numerous harmless ones which arise together with main products in processes of joint production, particularly as coupled outputs, and which may be desirable and perhaps may evolve to innovative main products themselves through research and development. However, the economic literature makes no distinction between (unintended) desirable byproducts and (intended) main products. Hence, economic theory seems to ignore the potential future prospects of harmless—as well as harmful—byproducts. This is in stark contrast to a large amount of literature on business, economic, and management aspects of byproducts in non-economic journals of many other applied academic research areas.

Climate change is the 'greatest market failure in history'. Carbon dioxide (CO_2) accounts for the largest share of greenhouse gas emissions, an unavoidable output of power plants in the course of the combustion (carbon oxidation) of the fossil raw materials coal, oil, and natural gas.[44] Economic theory uses the concept of external costs that need to be internalised to address market failures. This is problematic, however, because external costs are hardly measurable on a regular basis, difficult to forecast, and it is complicated to evaluate them. The mentioned greenhouse effect is a prominent example. It is based on a complex chain of impacts of emitted gases

[42] Strebel (1978) and Fandel (1981) were among the first.

[43] Regarding the topic 'joint product(ion)', 36 articles have been published since 1974 until 2020 that are assigned to the WoS categories 'Business' and 'Business Finance', with merely four journal articles since 2016. Five of the 10 most frequently cited of these papers appeared in journals specialised in business and finance (Anderson and Danthine (1980), Gilligan and Smirlock (1984), Mester (1992), Berger et al. (1993), Pulley and Humphrey (1993)), all of them concerned with banking and financial service. However, three of the 10 most frequently cited ones are published in the *Journal of Environmental Economics and Management*.

[44] Namely as chemical compound of carbon (C) and oxygen (O), where the input of oxygen is usually ignored as 'free good' in economic analyses.

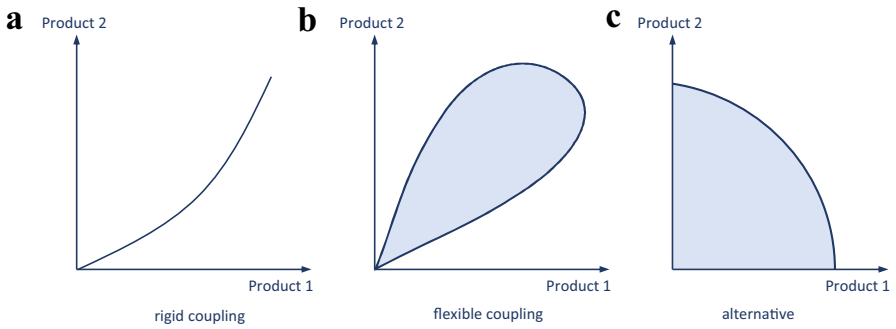

Fig. 4 **a** Rigid and **b** flexible coupled production; **c** alternative production (Dyckhoff 2021)

to nature and mankind, some of which are very long-term and difficult to assess. Nonetheless, the coupled outputs that cause the impacts ('external effects'), which in turn lead to the external costs, are not at all addressed by general economic theory. This deficit is all the more astonishing and disappointing because the damage to planet Earth's ecosystems by unintended outputs of production (and consumption) has become an existential threat to human civilisation since the beginning of the Industrial Revolution (two centuries ago).

The disclosed gaps are the result of the wide neglect of joint production and its various kinds of outputs in main-stream economic theory as well as of the lack of standard notions for its different manifestations. Such a poor clarity, imprecision, and inconsistency regarding established terms and concepts may lead to insufficient external validity of widely accepted models. Moreover, in the literature that is captured by the Web of Science, there are neither general reviews of business, economic, or management aspects of joint and particularly of coupled production, nor are there any approaches to an encompassing and general economic theory explaining the important empirical phenomena connected with these production types.

These gaps also reflect an excessive focus of academic disciplines concerned with business, management, and economics on those problems which are currently of economic interest, whereas other issues that may be marginal today but are likely to be of crucial importance in the near future are neglected. This suggests a persistent tendency towards a myopic approach to research strategies and a low appreciation of empirically validated (theoretical) basic research in general (production-based) economic theory.[45]

[45] Cf. Vanberg (2021, p. 277): "Today, economics presents itself as a highly equipped empirical science that can hardly be accused of model platonism. However, its research efforts are largely limited to dealing with a wide variety of individual questions, the selection of which seems to be made more according to the availability of data than in the light of theoretical questions, and the significance of the research results seems to be measured more by the sophistication of the analytical techniques used than by the relevance of the problem. Much less attention is devoted to making clear how the diverse research efforts can be categorised and linked within the framework of a comprehensive, empirical theory." (own translation from German).

"Social being determines consciousness!" This well-known assertion by Karl Marx seems to apply analogously to the economic sciences insofar as their dominant paradigms and fashionable topics, or rather their protagonists, concentrate on the respective current economic questions and thereby overlook, forget, or relegate other topics to the sidelines, as long as they are not taken seriously by today's economy and society. At least, such a conjecture becomes obvious in the course of the historical analysis concerning the attention (not) paid by the prevalent theories of economic sciences to—in real terms always omnipresent—coupled production. This is an omission that seems to persist largely until today.

There are also some deficits in the strongly increasing research in specialised economic fields that deal with undesirable outputs—and thus usually also deal with coupled outputs (without addressing this fact explicitly). Much of this literature is concerned with performance measurement, particularly with data envelopment analysis (DEA) as popular method (cf. Sect. 3.3). Avkiran and Parker (2010, p. 4) asked more than a decade ago: "given the popularity of DEA in academic journals, how widespread is its use in existing organizations?" Most of the 'applications' of DEA published in the academic literature are mere calculations with real data, but they do not demonstrate the actual benefits of DEA for the potential user. We suspect that a lack of convincing success stories is the real reason why DEA has not yet gained acceptance in *management accounting and control*—the area of business economics that is particularly concerned with performance evaluation. Therefore, a future research path regarding DEA and other methodologies measuring the performance of joint production should confirm more convincingly, through a sound empirical validation, that their application really matters and can improve real life.

In order to bridge the conceptual and theoretical gaps, an economic theory is needed that is generalised—and empirically better founded—in such a way that allows to explicitly cope also with all non-market phenomena that are (or might be) important, especially those caused by or resulting in resource scarcity, declining biodiversity, climate change or other severe damage to natural foundations of human life. Dyckhoff and Souren (2022) developed a framework (outlined in Fig. 3) for a (decision-based) multi-criteria production theory which allows to answer the following and other questions that cannot be meaningfully answered by traditional economic theory (Dyckhoff 2022):

- Which types of (physical or immaterial) objects are to be considered at all in a theoretical or practical analysis? To what extent does object quality play a role and thus define different types or varieties, e.g. in waste sorting?
- To what extent do the outputs of a waste incineration, an end-of-life vehicle dismantling or (in general) a 'reduction' of bads constitute coupled outputs?
- How can efficient production be defined if surpluses of main products are not desired or if the preference for byproducts depends on their quantity or (unknown) usefulness? Can inefficient production be rational at all?
- Does it always make sense to prioritise avoiding unintended outputs over their recycling or disposal (as often requested by law, e.g. the German *Kreislaufwirtschaftsgesetz*)?

- Which model approaches are suitable for the management of material and energy flows in different types of flexible coupled production?
- What analogies exist between the allocation principles of business accounting and those of environmental management (according to ISO 14040/44)? How can the findings of cost accounting be used to improve the allocation of environmental damage to coproducts in life cycle assessment (LCA)?

A variety of papers on such questions have been published in the past years, but mainly in journals of disciplines, which, in accordance with their traditions, make little reference to theories of (business) economics, especially not explicitly to 'joint production' (e.g. the *Journal of Cleaner Production* or the *International Journal of LCA*).

Looking back on the development of economic ideas, it has become obvious that joint production—and notably coupled production—was never really at the centre of discussion but was an important marginal topic for the classics in the days of the agricultural economy. Industrialisation facilitated the exploitation of fossil raw materials and provided cheaply available primary energy for production and consumption. In the past century, the natural environment of the continents, the oceans, and the atmosphere of 'spaceship Earth' could be used for waste, sewage, and exhaust gases seemingly 'free of charge'. Thus, with the neoclassic research paradigm, coupled production almost completely disappeared from the field of economic science. Only in recent decades, with the increasing external costs caused by environmentally harmful coupled (joint) outputs, did it regain a limited importance as a marginal topic, thanks to specialised economic sub-areas such as environmental and welfare economics or corporate sustainability and production management.

A fundamentally new approach to the subject could be to generalise it in such a way that coupled outputs are not only analysed from the narrow perspective of production, but that investigations are further expanded to all human actions considered by the economic sciences, especially also to consumption (Dyckhoff 2022). This can be achieved if rationality is no longer narrowed down to the two categories of the intended (main) *ends* and the *means* employed, as is generally the case, but if the possible *secondary results* of an action are also included in the evaluation as a third category (as it is known of medicines: "No effect without a side effect!"). Thus, unavoidable secondary results are to be classified as (impacts of) coupled outputs of the action (perhaps the end-of-life product after its consumption or usage). Such an expanded perspective would correspond to the original concept of purpose rationality according to Max Weber (1921).

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