

A framework for studying outcomes in industrial symbiosis

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ABSTRACT

It is likely that different industrial symbiosis collaborations will have different sets of winners and losers when it comes to benefits or costs. In this study we present an analytical framework intended for evaluating a wide-range of industrial symbiosis outcomes that will aid in research design. The framework provide a base for including a broader, but also, specific set of effects and outcomes (economic, environmental and social), including a diverse set of clearly defined actors. Used consistently, the framework can average out costs and benefits across actors in the whole society, so that each actor is more likely to (over time) realize net positive outcomes from a full set of industrial symbiosis applications. The analytical framework is developed by combining theory and concepts from the system of national accounts, the planetary boundaries, and the social foundation. The analytical framework is then applied in a state of the art review, analysing value and benefits in 56 industrial symbiosis research articles. Besides providing a robust model for analysing industrial symbiosis, the results show that private market-based outcomes are the dominant form of economic value and that nonmarket valuations are completely absent. Environmental outcomes mainly consist of decreased CO₂ emissions, chemical pollution and water use. Social outcomes include private income and work and network effects for the companies involved in the industrial symbiosis.

1. Introduction

Industrial symbiosis has gained significant attention in the past few years, as can be seen both in practice and in the number of research articles, which has grown exponentially [1]. Industrial symbiosis is a subfield within industrial ecology which studies physical flows of energy and materials in society [2]. In the industrial ecology paradigm, industrial activity is no longer viewed in isolation, but instead as a larger system of interconnected industries or processes [2–4]. The essential core of industrial symbiosis is cooperative sharing of resources such as energy, material by-products, wastes and water [3]. Economic and environmental benefits have, by definition, been central concepts in industrial symbiosis from its inception [5]. The generally accepted definition of industrial symbiosis is that there are ample economic, environmental and social benefits originating from material exchanges and other shared resource flows, both between and within industries [6].

In the context of combating climate change, industrial symbiosis is closely linked to sustainability and sustainable development [5] and is considered an important strategy for transitioning towards a circular economy [7]. Sustainable value is often treated as a general phrase to

express positive effects related to business results [8], although the circular economy is trying to steer away from the linear economy, with its accompanying unsustainable production and consumption, by balancing the three dimensions: society, environment and economy [9]. On a practical level, industrial symbiosis has been identified as a promising solution for improving environmental sustainability while simultaneously achieving economic benefits [10], and the development of industrial symbiosis is part of the EU's sustainable industry policy programme [11] and the Green Deal [12]. Achieving the European Union's climate and environmental goals requires an industrial policy based on a circular economy [13]. The circular economy, including the industrial symbiosis concept, can be considered a global mega trend and the EU's strategy for becoming the world's first climate neutral continent by 2050 involves several ambitious policies in which sustainable industry plays an important part. Amongst many challenges for achieving a sustainable future, one very important one is understanding the changing ideas about value [14] and the value creation process [15]. Industries will have to respond to environmental, economic and social challenges by considering sustainable value in their business models [16]. Moreover, the ability to understand and capture sustainable value will be a crucial ability for industry in terms of capturing value for itself

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while also delivering value for multiple stakeholders and the environment [8].

1.1. Measuring industrial symbiosis

Much effort has been put into identifying common terminology and trying to provide a typology for industrial symbiosis; and this has resulted in many theoretical and conceptual frameworks such as comprehensive reviews [1], taxonomies [3], comparative frameworks [17] and bibliometric analyses [18]. In addition to finding a common definition of industrial symbiosis, attention has been focused on measuring and analysing the performance and outcomes of the practice of industrial symbiosis [19]. Frequently studied areas are economic and environmental effects [20], were benefits traditionally being the goal in industrial symbiosis applications [21], and who the recipient of these benefits are [22]. Furthermore, in the closely related research field of process integration, much attention have been given to sustainable design of energy systems [23], the techno-physical potential of integrated multi-product systems [24] and circular integration processes [25]. Recent studies advance the knowledge regarding indicators for evaluating and assessing industrial symbiosis synergies, focusing on sustainability [26]; where and how to measure industrial symbiosis and indeed what to measure [7]; and micro level indicators for a circular economy [9]. These studies present valuable contributions central to the understanding of how to design a more sustainable industry and provides essential assessment indicators and evaluation methods. There are some examples of literature providing standards for evaluating industrial systems on the meso level. For example, the world Bank framework for requirements and performance criteria for eco-industrial parks [27] China's Eco-industrial park standards [28]. Additionally, other frameworks include measures of stocks and flows in combination with various capital concepts e.g. natural- and human capital e.g. Ref. [29]. However, the frequent focus on actors and details within the scope of the synergy, (e.g. input output models [30]) can potentially exclude important outcomes and potentially affected actors. Thus, there is need for a framework that can explore outcomes beyond the synergy itself and include actors from the whole economy. A framework that can identify winners and losers across time and space with regards to economic (costs and benefits), environmental and social impacts [31]. To the authors' knowledge, no one has compiled a model for aggregation and analysis of outcomes found in industrial symbiosis that also includes the whole economy. Much less providing a detailed analytical framework for the comprehensive understanding of outcomes and economic benefits based on national account principles and taking the lifetime of synergies into account. In other words, there are ample studies of indicators for evaluating industrial symbiosis synergies and, for example, eco-industrial parks, but not for strategically evaluating the overall societal economic impacts generated by industrial symbiosis projects. In this paper we present an analytical model that helps to understand how outcomes in industrial symbiosis literature are derived and what actors in society that are included. The analytical framework is based on the concepts of economic value rooted in economic theory and the principles of national accounts [32], ecological outcomes based on the planetary boundaries [33] and social outcomes based on sustainability concepts and practices [34] and the sustainable development goals [35]. By applying the framework, the study is examining the characteristics of the outcomes in industrial symbiosis literature, as well as pointing out research gaps and identifying future areas of research.

2. Aim and scope of study

The main aim of this paper is to (1) present an analytical framework that will support the assessment of a wide-range of industrial symbiosis outcomes and aid in research design. The process, in which the study develops the analytical framework, is inspired by the content analysis methodology. And (2), the study will test the analytical framework by

applying it in a state of the art review of industrial symbiosis research. The review examines outcomes found in industrial symbiosis research and the process in which outcomes have been identified and derived. The reason for delimiting the review to industrial symbiosis, by not explicitly including related literature from other research fields such as circular economy and process integration, is to first test the framework. This opens up for applying the framework on other research fields separately (see Fig. 1) whereby increasing the ability to make comparisons between them. The purpose of the analytical framework is to categorise outcomes, key actors and elements in industrial symbiosis research by situating them into well-established concepts. As the spatial boundary is vital when assessing an industrial symbiosis, an analytical framework is required to operate on any system level. In this regard, the framework follows the macroeconomic principles of national accounting and provides a bottom up structure for strategic insights into the environmental, social and economic outcomes. This will enable for maintaining consistency and transparency when compiling measures for sustainable industrial production. Applying the framework will expand the understanding of economic value — by distinguishing between market and nonmarket valuations — and by extension, the possibility to assess the alternative cost of establishing synergies. Also, by including the social foundation (doughnut economics [34]) and planetary boundaries [33], outcomes in the literature are directly linked to vital aspects for a thriving society and stable earth systems. The exemplifying state of the art review answers the following research questions:

- What methods, and combination of methods, are used in previous research to study industrial symbiosis and what institutional units or sectors are studied (for example corporations, industries, plants, government, and households)?
- What types of symbiosis categories (energy, material, by-products, waste and water) are studied and what type of outcomes (limited to value and benefits) are identified (economic, environmental and social) in relation to the symbiosis category and in the analysed timeframe?

Although this study examines positive outcomes – such as economic, environmental and social benefits – it should be made clear that the industrial symbiosis concept is not without critique. And even though the concept is a well-established research field, negative impacts and trade-offs from industrial symbiosis have not yet been extensively explored [36]. For example, environmental benefits from recovering materials may not offset the negative impact generated by waste management activities [37]; the trade-off, or contradiction, between recycling and energy efficiency, or recovering expensive materials with low environmental impact rather than vice versa [38]; trade-offs between the potential uses of waste resources based on economic factors rather than environmental aspects [39] and the risk of prolonging environmentally detrimental industrial activities that would otherwise have discontinued without industrial symbiosis.

3. Constructing the analytical framework

In order to construct the analytical framework used to understand the mechanisms of how outcomes are derived in industrial symbiosis, there is need to know how effects are identified and measured. In order to do this, the study uses a methodology inspired by the content analysis method. Content analysis or qualitative content analysis (QCA) is a systematic approach that enables researchers to quantify and analyse the presence, meanings and relationships of words and concepts in the studied data and then draw conclusions about the underlying meaning or message [40]. Basically, content analysis is a way to systematise the understanding of texts and other material, with the goal of achieving an overview of the meaning in the material and, in terms of method, increasing the intersubjective understanding of the material [41]. The coding and analysis were then carried out in the computer software

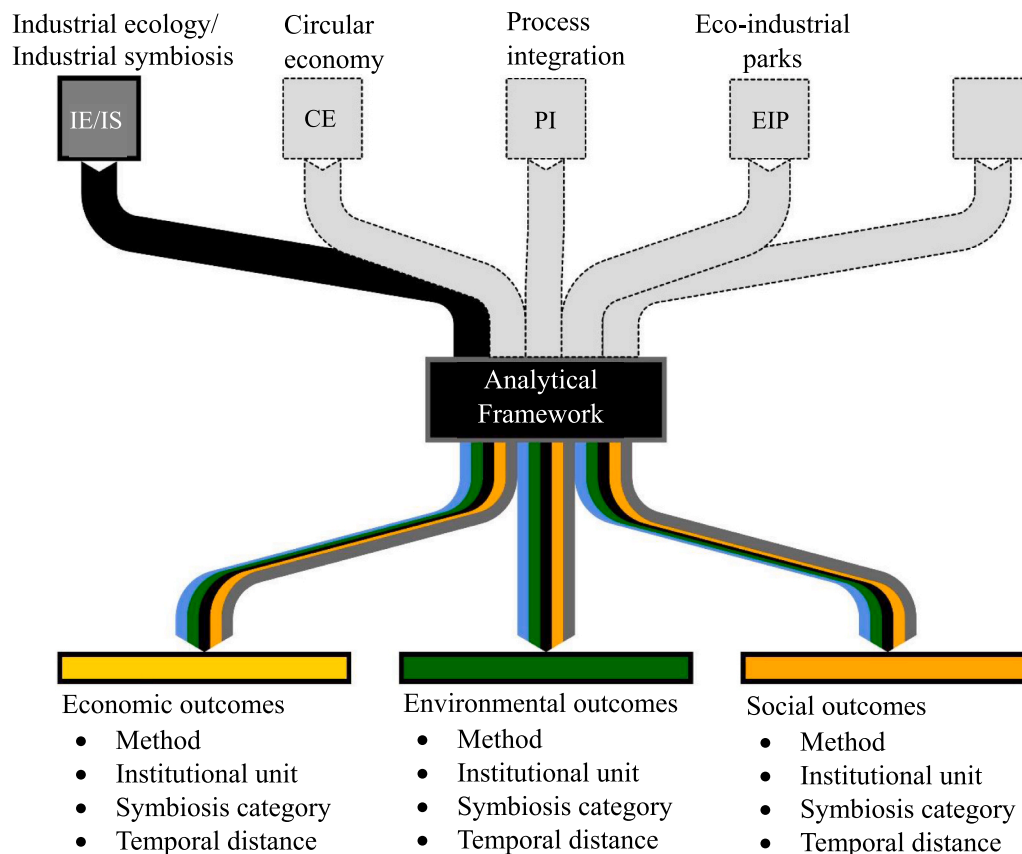


Fig. 1. An overview of the analytical framework capable of analysing a broad range of outcomes. The review in this paper studies industrial symbiosis (focusing on value and benefits).

NVivo 12 pro.¹

The coding framework used in this paper was developed using both concept-driven (deductive) and data-driven (inductive) strategies. The deductive strategy draws from economic theory and the statistical principles of UNSC national accounts [32] in combination with the conceptual framework of social boundaries [34], planetary boundaries [33,34] and climate tipping points [42].

The procedural steps of the analysis include (1) deciding the research question, (2) selecting texts and documents, (3) constructing the coding frame, (4) dividing the material into units of coding, (5) testing the coding frame, (6) evaluating and modifying the coding frame, (7) main analysis, (8) interpreting and presenting the findings (for details see Fig. 2).

3.1. Selecting documents for analysis

Although the analytical framework is capable of analysing a broad range of outcomes, both positive and negative, this study focuses on value and benefits in current industrial symbiosis literature. The reason for this delimitation is to deepen the analysis, centred around the core objective in industrial symbiosis, which is to deliver economic, environmental and social gains and benefits [3,4,43]. Thus, the scope of the study includes research outcomes conforming to the defined goals of industrial symbiosis. In this paper, the word “value” is considered to be any desired and identified effect originating from an industrial symbiosis synergy. Furthermore, the concept of value in this paper refers more to the economic concept of assigned value, rather than the underlying

concept of held value [44] that is sometimes manifested in e.g. monetary value [45]. Thus, this paper study the occurrences of the broader concept of economic value and outcomes in industrial symbiosis research, and outcomes can be expressed as a value or as any expressed benefit, gain and desired effect. Faced with large amounts of qualitative data in the form of text and documents, extracting representative material can be notoriously difficult [46]. In order to use the content analysis method with validity and reliability, and without over-interpreting the studied material [47], there is need for actively picking studies that uses the terminology value and benefit. Thus, the sample in this study is by no means exhaustive and should not be seen as all-encompassing. Instead, the study is a first step on a continuous effort understanding outcomes and the process of deriving value in developing a sustainable industry. Future applications of the framework should focus on expanding the sample by including articles from related research fields.

The studied documents (articles) are collected on the Scopus database, one of the largest databases for published academic research. The initial search query focuses on the document title, abstract and keywords (See Fig. 3 for more details). Boolean operators in combination with the wildcard function are used to capture all documents that contain loose phrase variations of the words value or benefit (e.g. value, values, valued, benefit, benefits etc.). The selected articles must also contain the words industrial symbiosis and so, the search query will contain two OR levels and one AND level.² In order to qualify for inclusion in the study, the articles must be based on cases, real or

¹ <https://www.qsrinternational.com/nvivo-qualitative-data-analysis-software/home>.

² For more details on document search see Scopus: Access and use Support Center: https://service.elsevier.com/app/answers/detail/a_id/11213/supporthub/scopus/#tips.

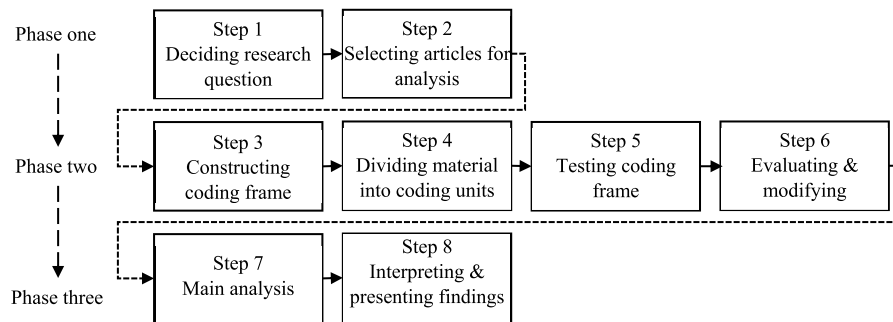


Fig. 2. An interpretation of the procedural steps in QCA presented by Margrit Schreier. The research questions in step 1 are presented in the aim of this paper and justified in the introduction. Steps 2 to 6 are described in more detail in the method section, while steps 7 and 8 are discussed in connection to the results, discussion and conclusion.

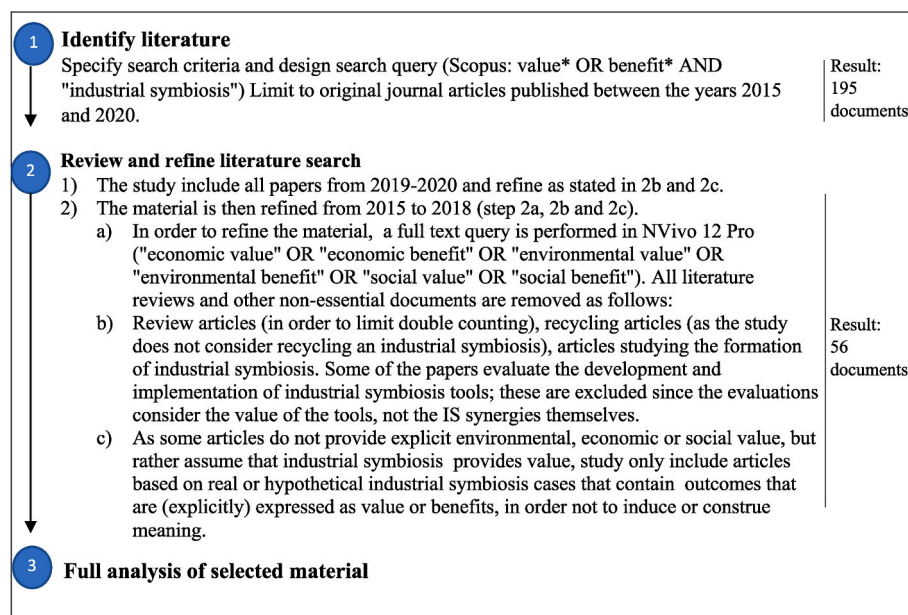


Fig. 3. Step two of the analytical framework: article selection.

hypothetical. Review papers are excluded in order to limit double counting outcomes and value. Also, some articles in the related research field of the circular economy are inevitable included in the study as the terms, industrial symbiosis and circular economy are often used simultaneously and interchangeably. Nonetheless, all articles must fulfil the scope criteria in order to be included.

After the initial search, the result is refined. Some industrial symbiosis articles do not provide clear evidence of environmental, economic or social value as the article do not present any form of causal chain or logic with regards to how outcomes are derived. These articles more or less assume and discuss the potential benefits of industrial symbiosis synergies without presenting any details. And thus, these articles are excluded from the study as these do not provide additional information. Also excluded by this principle are articles studying the formation of industrial symbiosis collaborations, as these study prerequisites for industrial synergies rather than the outcomes. Articles that evaluate, develop and implement industrial symbiosis tools are excluded since the studies do not focus on the actual synergy. The exclusion is motivated by the fact that the articles consider the value of the tools, not the value of industrial symbiosis synergies. Articles studying recycling are outside of the scope and are thus excluded.

3.2. The coding frame

There is only one main category in this paper as it will only consider the outcomes related to the goal of industrial symbiosis, which is to deliver various economic, environmental and social benefits [5,43]. As mentioned before, the coding frame is general and can be used for analysing any effects stemming from industrial symbiosis or closely related research fields. However, in this paper, only the desired outcomes (values and benefits) are studied. Building the general coding frame (see Fig. 4) involves deciding the structure of the main category (black box), which also acts as the research questions. The main category is then broken down into clear segments conceptualised by the subcategories (grey and white boxes). The coding frame will be a mixed strategy approach, using a dominantly concept-driven (deductive) strategy for deciding subcategories. Moreover, subcategories are broken down into several detailed coding frames, with a number of additional subcategories. From a general point of view, it can be assumed that outcomes presented in the research articles to a significant extent depend on the choice of method. Thus, the study examine what research method or methods are used; what is the studied object or institutional unit; the symbiosis category or categories that occur in the articles; the outcomes or results from each study; and what time horizon each study analyses. The coding frame is constructed with the specific purpose of capturing the occurrence of the specified categories presented in this

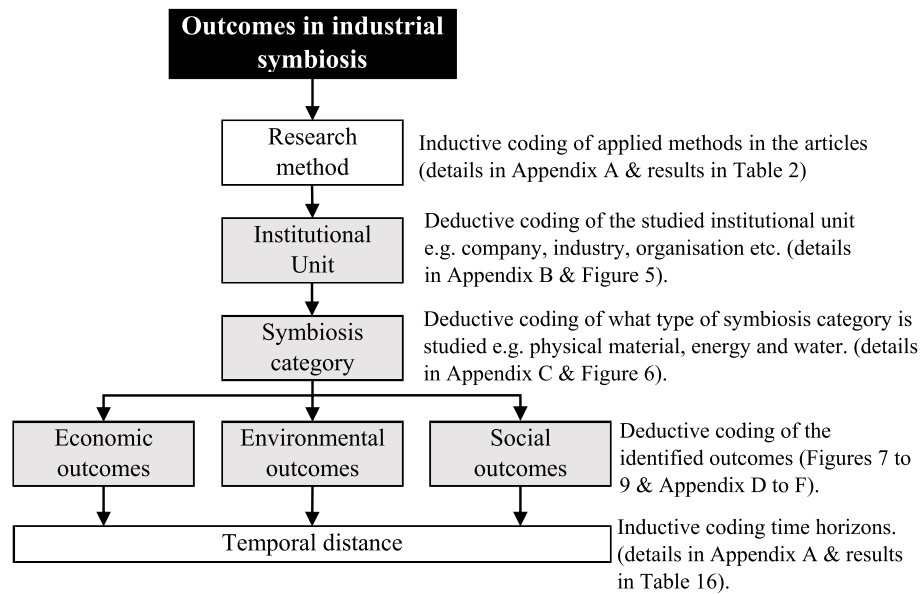


Fig. 4. The main category in the analytical framework (Outcomes in industrial symbiosis research) is broken down into the seven subcategories: Research method, Institutional unit, Symbiosis category, Economic/Environmental/Social outcomes, and Temporal distance. The deductive subcategories (grey boxes) will also be broken down into further subcategories (Fig. 5 to 9). The subcategories with inductive coding (white boxes) will only be presented in the results section.

chapter. And thus, it is presumed that each article may contain many of the categories, although the lack of occurrences of certain categories is also considered an important result. Detailed information regarding each coding frame, including definitions, examples and (when needed) coding rules, can be seen in [Appendices A to F](#).

3.2.1. Methods and temporal distances

The subcategories Research method and Temporal distance (white boxes in [Fig. 4](#)), inductively examine what method or combination of methods each article is using, and the different time horizons used in the analysis in the articles (see [Appendix A](#)). For an industrial symbiosis that has effects over several years, there is need for a way to aggregate and compare outcomes that occur over time. There are several reasons for this. First, there is always an opportunity cost to the resources used in order to implement and sustain the synergy. Second, people (institutional units) often prefer to consume at the present rather than later. Third, there is always uncertainty surrounding the ability to obtain future value. Thus, there is need for a framework that can analyse society as a whole and the willingness for trade-offs between present and future benefits [31]. Choosing research method and timeframe for the analysis will to a large extent determine the results. Therefore, these subcategories are essential for understanding the fundamentals of deriving outcomes and value in the selected literature.

3.2.2. Institutional unit

In order to understand where researchers look for benefits or value, and where these are generated or realised, there is a need to examine the institutional unit in the research articles. In this paper, the institutional unit together with the industrial symbiosis synergy form the basis for any outcome. The categories in this part of the coding frame ([Fig. 5](#)) follows the definitions and categorisation in the system of national accounts (SNA). According to these definitions: an institutional unit can be defined as an economic entity that is capable, in its own right, of owning assets, incurring liabilities and engaging in economic activities and in transactions with other entities [32]. Institutional units are grouped together in sectors based on similar characteristics and economic behaviour. [Fig. 5](#) illustrate the allocation of units into sectors based on the definitions in the national accounts. The main advantage using the SNA when assessing industrial symbiosis is that the analysis is placed directly into one of the most extensive frameworks for measuring economic activity. The distinction between market and nonmarket producers provide the necessary distinction for the sake of evaluating how value is perceived and where in society it is realised. Market producers are entities where all or most output is either output for sale or output for own use. Any reference to private or public corporations, companies, firms and enterprises etc. will be categorised as a market producer. Furthermore, there will be a distinction between private and public-private market producers (for more details, see [Appendix B](#)). A

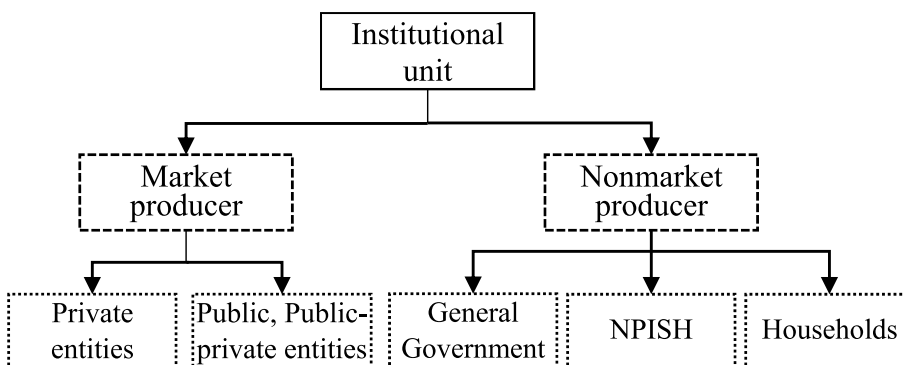


Fig. 5. Coding frame for institutional units found in industrial symbiosis literature, based on the national accounts. Subcategories are a simplification of the five mutually exclusive sectors defined in the systems of the national accounts framework. Market producers can be both public and private units. Nonmarket producers are producers that provide most of their output to others free or at prices which are not economically significant. General government mainly contains central, state and local government units. NPISH stands for non-profit institutions serving households – examples include churches and religious societies, sports clubs, trade unions, political parties etc. Households consist of individual persons, or groups of persons, providing themselves with food or other essentials for living.

strong indicator that an institutional unit is a market producer is that market prices are used for valuation (monetarisation) in the article. Nonmarket producers are defined as establishments owned by the government or by non-profit institutions serving households (NPISH) that supply goods or services free, or at prices that are not economically significant, either to households or the community as a whole. Studying households is of vital importance as households comprise a large part of the informal global economy. In 2018, the share of women and men participating in the informal economy constituted around 60% of the global population [48].

3.2.3. Symbiosis category

Fig. 6 presents the part of the coding frame that examines the type of symbiosis studied in each article. The coding is rather straightforward, assigning units of coding to the three subcategories based on what type of industrial symbiosis synergy is included in the articles. All energy-related synergies, such as excess heat or steam exchanges and energy from the use of waste or other by-products, are assigned to the energy subcategory. All physical material flows that are not an energy synergy will be assigned to the subcategory material, by-products and waste. And finally, all units of coding referring to water synergies will be coded in the water subcategory. For more details regarding definitions and coding, see Appendix C.

3.2.4. Economic outcomes

In this part of the coding frame (Fig. 7) the economic outcomes are categorised, as either market-based or nonmarket-based valuation. Any outcome based on economically significant prices or market prices [32] are considered market-based: for example, a unit of coding containing any generation of economic outcomes such as reductions in cost, financial benefit, increased or extra revenue, decreased cost, additional value, competitive advantages. In this paper, nonmarket valuation is defined in line with the concept of Total Economic Value [49], which estimates the value for either goods or services that are not traded for money but are valued in terms of what people are or would be willing to pay rather than go without them [45] for example, fish and wildlife value and scenic quality value. For more details regarding definitions and coding, see Appendix D.

3.2.5. Environmental outcomes

In this part of the coding frame (Fig. 8), outcomes identified as environmental are categorised. When focusing on values and benefits, such outcomes can for example be reductions in GHG emissions, reductions in waste discharge and decreased water utilisation. Environmental value must originate from an identified symbiosis and be clearly distinguished from other effects in the articles. This means that effects are either quantified or explicitly mentioned. This part of the coding frame consists of nine environmental subcategories based on the sustainability approach of planetary boundaries presented by Rockström, Steffen [33]. The motive for this is that it will enable outcomes in industrial symbiosis research to be directly and clearly linked to Earth's life-supporting systems and its ecological limits. By assigning outcomes in industrial symbiosis to these categories, it is possible to analyse them in more detail and with clearer implications. For more details regarding

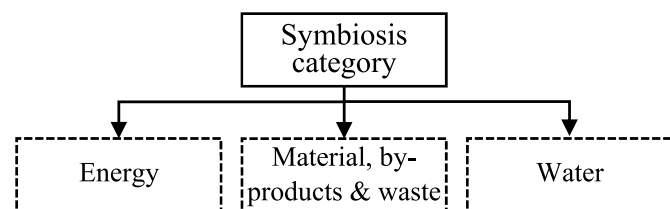


Fig. 6. Units of coding containing type of industrial symbiosis synergies will be categorised into energy, material, by-products & waste and/or water.

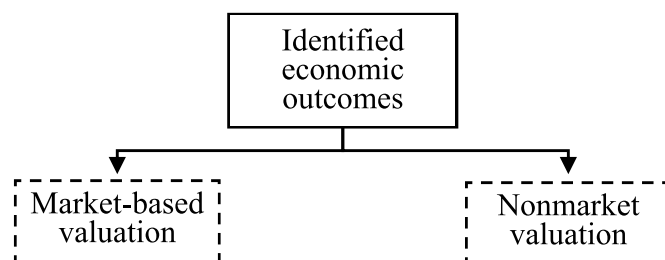


Fig. 7. Coding frame dividing the economic outcomes in the articles into market and nonmarket valuations or benefits, based on the definitions in the system of national accounts.

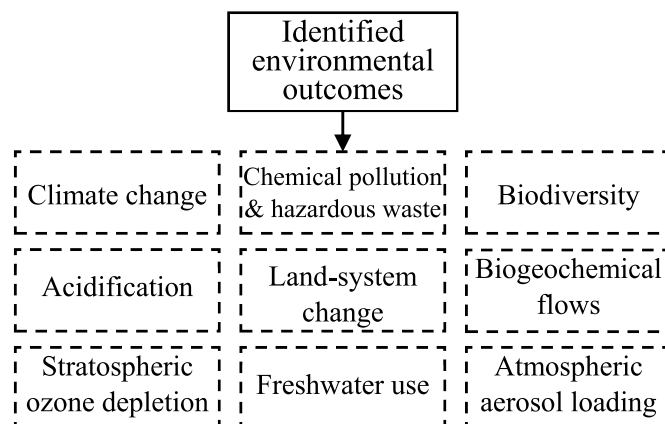


Fig. 8. Coding frame regarding the environmental outcomes with categories based on the planetary boundaries presented by Rockström, Steffen.

definitions and coding, see Appendix E.

3.2.6. Social outcomes

The outcomes related to social aspects are presented in Fig. 9 and the subcategories are based on the standards for human wellbeing [35] and the framework of the social foundation [34]. The purpose for using the social foundation as categories for the analysis is that it presents a

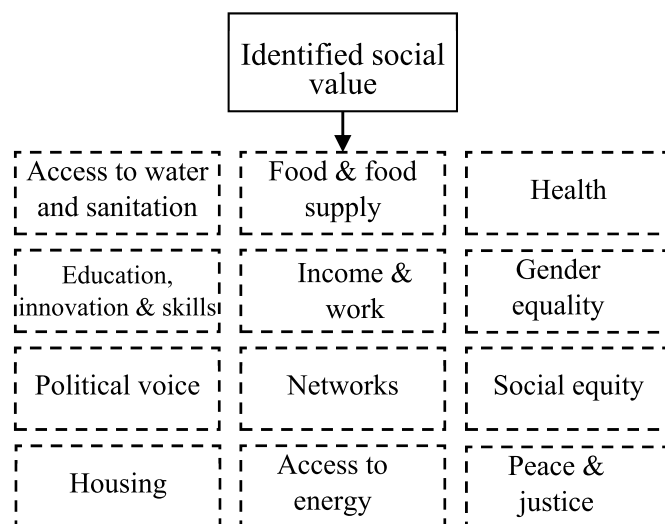


Fig. 9. Coding frame of the social outcomes with subcategories based on the framework of the 12 dimensions of the social foundation conceptualised in A Doughnut for the Anthropocene: humanity's compass in the 21st century by Raworth. The social priorities are specified in the United Nations Sustainable Development Goals from 2015.

well-defined structure for assessing social outcomes in industrial symbiosis research. By using the planetary and social boundaries as environmental and social subcategories; the analysis is able to strategically evaluate how outcomes from industrial symbiosis research are meeting the environmental and social needs in order to develop a sustainable society. For more details regarding definitions and coding, see [Appendix F](#).

3.3. Dividing articles into segments and coding

The disposition of the content in the studied articles generally follows established academic styles, with sections such as introduction, background, results, analysis and conclusion etc. This will greatly help in the segmentation procedure, as the articles will have more or less predefined segments, making coding more or less explicit. The coding is performed by assigning units of coding from the unit of analysis into the coding frame categories (see [Fig. 10](#)). The unit of analysis is the research articles (not to be confused with institutional unit) and the units of coding are the smaller segments within the articles. The coding procedure uses a mix between formal and thematic assignment criteria. The content in the articles is broken down into sections, paragraphs, phrases and words, where words are the smallest units of coding possible. The formal criterion means that segmentation and coding is done by first selecting a section then a paragraph, studying the occurrence of method, institutional unit, symbiosis category, outcomes and value and time horizon. The thematic part of the criterion means that a unit of coding starts with a statement containing the studied category and continues until a change of topic. Each coding unit will only fit into one of the subcategories under the main category, which means that units of coding are mutually exclusive when it comes to assigning the segment to categories. The analysis will only consider the occurrence of categories in each article (e.g. the occurrence of a certain method, institutional unit or outcome) and not the frequency of the content (the number of times the method or institutional unit occurs in each article). The coding will be either deductive or inductive coding, as presented in [Fig. 4](#).

3.4. Testing, evaluating and modifying the coding frame

In order to test the coding frame and evaluate validity and reliability, a test coding was performed in a pilot phase, and this was done by three researchers independently. The pilot test results showed higher conformity between two of the coders, calling for adjustments in both the coding frame and the coding procedure. In order to increase the accuracy of the coding frame, definitions were expanded and clarified and detailed examples were provided. Additional adjustment included introducing coding rules for further clarification of how to code. The coding procedure was adjusted so that only explicit content, strictly adhering to the coding criteria, would be allowed to be assigned to categories. The combined adjustments increased the coding precision, by restricting subjective interpretations involving “reading between the lines” or overinterpreting the intended meaning in the articles, while simultaneously limiting loss of material richness. After the test coding, the main analysis was performed by the main author of this paper. When performing a content analysis using a single coder, there should be consistency between different points in time. Therefore, a second coding was performed two weeks after the first analysis. The comparisons showed high consistency and only small changes in the assignments of units of coding were done, while the coding frame and coding procedure were kept unchanged.

4. Results and analysis

The result and analysis is presented by first providing a general overall view of the study of industrial symbiosis research. This overview is created by following the structure of the general coding frame presented in [Fig. 4](#). The overall view outlines and summarises the study. However, its general structure loses some of the important details and thus it needs to be complemented by detailed results. Hence, after the general results are presented, the findings are described in detail by presenting the results in accordance with the subcategories from the coding frames presented previously in [Figs. 5–9](#). The order in which the results are presented and analysed can be seen in [Fig. 11](#) below, where

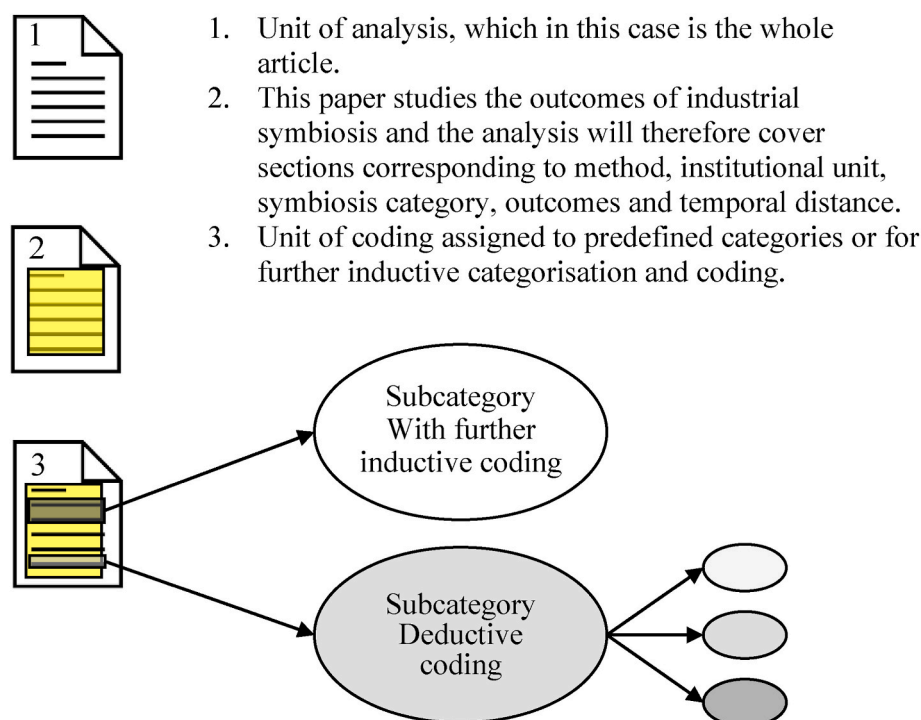


Fig. 10. Coding procedure where deductive coding categories are defined by previously defined theories and concepts, while inductive categories explores the content more freely.

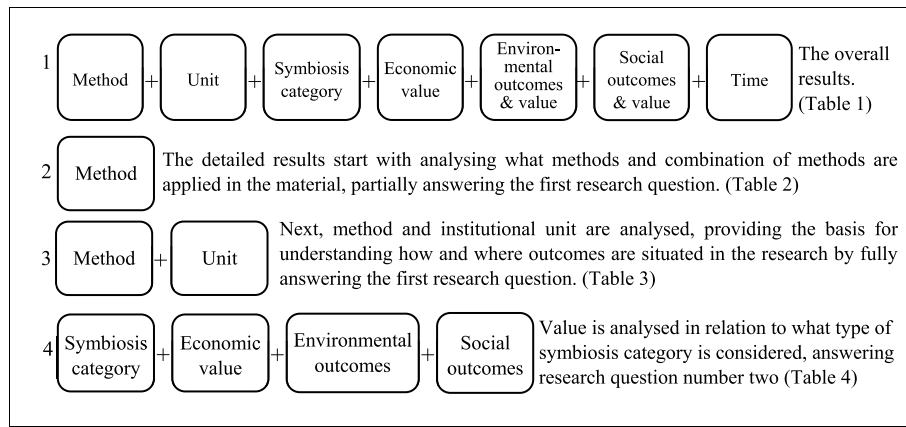


Fig. 11. The figure displays the order in which the results will be presented and analysed. In order to acquire a thorough understanding, the section first presents the results from the full perspective of the general coding frame (see Table 1). The result section then present and analyse the detailed results, according to the structure 2 to 4 in this figure, where the research questions will be answered in full.

step 1 presents the components in the overall results and steps 2 to 4 present the components of the detailed results. Appendices G to M present tables linking subcategories with their associated article references.

4.1. Overall results

The results in Table 1 show the overall results, presented using the structure of the general coding frame in Fig. 3. One striking finding from these results is the total absence of nonmarket valuation in the studied

Table 1

Overall results of the study. Outcomes are limited to desired effects i.e. value and benefits. The general overview of the results according to the layout presented in the general coding frame in Fig. 4, where the colour shading ranges from red, indicating no occurrences in any articles, to green, indicating the maximum number of articles with occurrences. Methods (row) and the incorporated aspects presented (column). In this table, neither rows nor columns should be summarised for totals, as the numbers represent occurrences, meaning that the same article can occur in several cells, thus distorting the sums.

Method	Institutional unit		Symbiosis category			Outcomes (value and benefits)				Temporal distance				
	Market producer	Nonmarket producers	Energy	Material, by-products & waste	Water	Market based valuation	Nonmarket based valuation	Environmental value & benefits	Social value & benefits	1-2 y	3-5 y	6-10 y	11-15 y	16+ y
Interviews	14	7	13	13	6	6	0	13	9	7	2	1	0	1
LCA	13	2	9	12	6	2	0	13	4	7	2	2	0	0
Case studies	10	5	7	9	4	6	0	10	7	5	2	1	1	0
Optimisation	7	1	4	6	3	3	0	4	3	3	2	1	0	0
Surveys & questionnaires	7	3	7	7	4	3	0	7	4	4	0	0	0	0
ABM	6	1	1	6	0	5	0	1	3	1	0	1	1	0
Other modelling & systems approaches	6	2	4	6	2	3	0	3	2	2	0	1	0	1
Document analysis	4	2	3	4	2	1	0	4	3	1	1	0	0	0
Focus groups & workshops	4	3	4	3	1	1	0	4	4	3	0	0	0	0
Game theory	4	1	2	4	1	3	0	3	1	0	1	0	0	0
Network analysis	4	1	4	4	2	1	0	3	2	1	0	1	1	0
Business models	3	0	0	3	0	3	0	2	1	0	0	0	0	0
Emergy & exergy analysis	3	1	3	2	3	0	0	3	0	1	0	0	0	0
I-O models	3	0	2	3	0	2	0	2	1	2	1	0	0	0
MFA	3	1	2	3	1	1	0	3	0	1	0	0	0	0
Other	10	2	6	10	2	7	0	9	6	2	0	2	2	1

articles. Furthermore, although outcomes in the articles generally indicate reductions in energy utilisation, decreased virgin material inputs and wastes, these were not quantified in a clear manner. Another finding is that many articles often provide no or unclear information regarding the time horizon (temporal distance) used in their analysis. This is also true for the articles applying life cycle analysis (LCA), where the temporal delimitation is an important factor for the analysis. In the articles clearly declaring time horizons, the temporal distance mostly varies between one and two years. In fact, only two studies have a clear timeframe greater than 16 years in their analysis (for details regarding temporal distance see Fig. 16 and Appendix M). The dominantly studied institutional units are market producers. However, nonmarket producers are mentioned in several articles, but mostly as a facilitator unit or unit performing a support function for industrial symbiosis collaborations rather than a unit partaking in the benefits or value accrued by the collaboration. Energy, material, by-products & waste synergies are the most studied symbiosis categories in the studied articles. Water synergies also frequently occur in the articles but almost exclusively as industrial wastewater synergies. It was revealed that many outcomes presented in the articles are related to environmental effects and the second most frequent are social effects. Economic outcomes, while diligently mentioned in the articles, are mainly descriptive in character, expressed in terms such as: increased revenues, decreased costs, increased income or in terms of competitive advantages. Very little is actually quantified in a structured manner and the economic outcomes that are quantified or monetised are exclusively performed using market valuation methods.

4.2. Methods used in industrial symbiosis articles

Table 2, provide the detailed results regarding what methods and combinations of methods are used in the articles and from reading the table diagonally, from the top left corner to the bottom right corner, there are roughly 25 different methods occurring, applied either by themselves or in combination with other methods in the 56 articles. Interviews are the most commonly used method, both as the main research method, exploring industrial symbiosis qualitatively, and as a data collection method for quantitative studies. Also, interviews are the method that is most applied in combination with other methods. The second most frequently used method is LCA, and some of the articles use LCA in combination with either Optimisation, Energy and exergy methods or input-output models (I-O models). The third most commonly used method is Case study research, often used in combination with Interviews. These methods are followed by Optimisation; Surveys and questionnaires; Agent based modelling (ABM) and Other modelling approaches; Document analysis; Focus groups and workshops; Game theory; Network analysis; Business models; Energy & exergy analysis; Input-output models; and Material flow analysis. The subcategory Other methods contains methods occurring only once (e.g. Sustainable value approach, EPOS methodology, Cost benefit analysis, Semantic artificial intelligence machinery and Techno-economic assessment). For more details see Appendix G.

4.3. Method and institutional unit

Table 3 shows the detailed results for the types of institutional units that occur in the articles. Market producers are the most studied institutional unit, occurring in all articles, whereas nonmarket producers

Table 2

Methods and combination of methods. Methods and combination of methods that are applied in the studied articles using inductive coding of explicitly stated research methods. The total number of occurrences for each method can be seen by reading diagonally (white cells) from the top left corner to the bottom right corner. The colour shading ranges from red, indicating no occurrences in any articles, to green, indicating the maximum number of articles containing the combination of categories.

	Interviews	LCA	Case studies	Optimisation	Surveys & questionnaires	ABM	Other modelling & systems approaches	Document analysis	Focus groups & workshops	Game theory	Network analysis	Business models	Energy & exergy analysis	I-O Models	MFA	Other methods
Interviews	14	2	6	0	7	0	2	3	4	0	3	0	2	0	1	3
LCA	2	13	0	1	1	0	0	0	0	0	0	0	1	1	0	0
Case studies	6	0	10	0	2	0	0	2	3	0	1	0	0	0	0	3
Optimisation	0	1	0	7	0	1	0	0	0	1	0	0	0	0	0	0
Surveys & questionnaires	7	1	2	0	7	0	0	2	2	0	2	0	2	0	1	2
ABM	0	0	0	1	0	6	1	0	0	0	0	0	0	1	0	1
Other modelling & systems approaches	2	0	0	0	0	1	6	0	0	0	1	0	0	0	0	0
Document analysis	3	0	2	0	2	0	0	4	1	0	1	0	1	0	1	0
Focus groups & workshops	4	0	3	0	2	0	0	1	4	0	0	0	0	0	0	1
Game theory	0	0	0	1	0	0	0	0	0	4	0	0	0	0	0	1
Network analysis	3	0	1	0	2	0	1	1	0	0	4	0	1	0	1	2
Business models	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0
Energy & exergy analysis	2	1	0	0	2	0	0	1	0	0	1	0	3	0	1	0
I-O models	0	1	0	0	0	1	0	0	0	0	0	0	0	3	0	1
MFA	1	0	0	0	1	0	0	1	0	0	1	0	1	0	3	0
Other methods	3	0	3	0	2	1	0	0	1	1	2	0	0	1	0	10

Table 3

Method and institutional unit In this table methods are presented by row and institutional units by column. As several methods and institutional units can appear in each article, neither rows nor columns should be summarised for totals. For totals see Fig. 12. The colour shading in the table ranges from red, indicating no occurrences in any articles, to green, indicating the maximum number of articles containing the combination of categories.

Method	Market producers							Nonmarket producers			
	Companies	Firms	Public & Private corporations	Hypothetical companies or firms	Undefined market producers	Factories, Plants, Producers, Suppliers & Retailers	Named	Industries	GGOV	NPISH	Households
Interviews	7	4	2	1	2	8	3	2	7	1	1
LCA	3	2	1	0	2	6	4	2	0	0	0
Case studies	5	3	1	0	2	4	1	0	5	1	1
Optimisation	1	1	0	2	0	2	0	2	0	0	1
Surveys & questionnaires	3	0	1	0	2	6	2	2	3	1	1
ABM	2	2	0	5	0	2	0	0	1	0	0
Other modelling & systems approaches	2	3	1	2	0	2	1	2	2	0	1
Document analysis	2	0	0	0	0	2	0	1	2	0	0
Focus groups & workshops	1	1	1	0	1	2	1	0	3	1	1
Game theory	2	2	0	3	0	1	0	0	1	0	0
Network analysis	1	2	0	0	0	1	0	2	1	0	0
Business models	3	2	0	0	0	0	0	0	0	0	0
Emergy & exergy analysis	1	0	1	0	0	3	1	1	1	0	0
I-O models	1	1	0	1	0	0	0	0	0	0	0
MFA	1	0	0	0	0	1	1	1	1	0	0
Other	3	5	1	2	1	1	0	2	2	0	0

occur in some articles (see Fig. 12). The studied market producers can roughly be divided into either individual units (such as firms or companies), or groups of units (such as industries). Again, several types of studied units can appear simultaneously in the articles, e.g. both market producers and nonmarket producers. However, studying the articles in greater detail the results show that the inclusion of nonmarket producers mainly serves the purpose of providing a background of the various actors involved in forming the industrial symbiosis or as a data source. Nonmarket producers are not a part of the core analysis quantifying and monetising outcomes. From Fig. 12, it is clear that the most frequently used terms utilised to define the studied institutional units are companies and firms, and the terms are often used interchangeably. Other types of institutional units that are commonly mentioned are factories, plants, producers, suppliers and retailers, which occur in several articles and in combination with almost all of the methods. Hypothetical and named market producers are also used frequently in the articles, with hypothetical units mainly appearing in ABM approaches.

Studying nonmarket producers, all three categories appear in the articles. However, government units are the most frequently occurring nonmarket institutional unit. It should be noted that even though nonmarket producers, such as government and NPISH, do occur the unit seldom partake in the outcomes in the sense that the institutional units directly contribute to or benefit from outcomes or value from the synergies. Nonmarket units rather exist as facilitators and perform support functions. Exemptions to these findings are Afshari, Tosarkani [50], who explicitly include benefits to households, and Fraccascia, Giannoccaro [51], who study the impacts of tax and economic subsidies on industrial symbiosis synergies. Additionally, there are many terms referring to unclear market and nonmarket institutional units, such as words or phrases just referring to, for example, private or public entities, actors, facilities and local communities. These units can of course be taken into consideration but were excluded in this analysis in order to restrict interpretation to more explicit content in the articles. References in Appendix H.

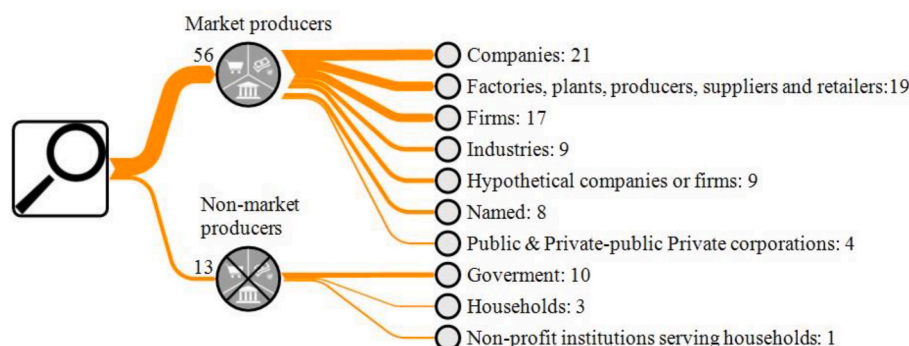


Fig. 12. The figure shows the total number of articles that contain institutional units defined as either market or nonmarket producers. All 56 articles contained market producers as the studied unit, compared to 13 articles containing nonmarket producers. The results show that only some articles include nonmarket producers in the analysis, mainly to describe the involved actors in an industrial symbiosis. Note that numbers of the individual types of institutional units do not necessarily correspond to number of articles containing market and nonmarket producers.

4.4. Symbiosis categories and outcomes

Table 4 and Figs. 13–15 presents the results regarding value and benefits in industrial symbiosis research in combination with the symbiosis category. The presence of the different symbiosis categories varies, and often two or all types of synergies occur together in the articles. Physical material synergies are the most common synergy in the articles, then energy synergies, followed by water synergies (Fig. 13).

The information and details vary regarding the materials and substances studied, sometimes making it difficult to perform an assessment of the outcome. Physical material synergies largely concern waste and the most commonly used terms or words describing this synergy category are waste, materials and resource synergies. Energy synergies are mostly just described as energy synergies, although steam and heat synergies are also mentioned. Water synergies almost exclusively involve industrial wastewater synergies, although there are a few that could be understood as being part of municipal wastewater treatment.

Economic value and benefits were discussed in almost all the articles, and the most frequently used terms for economic outcomes include lower input purchase cost, increased revenues, decreased cost from substituted materials, selling underlying resource, avoided taxes, lower production cost, reduction in waste disposal cost and increased profit etc. However, even if economic outcomes are more or less assumed in all articles, only 28 of them quantify, monetise or in other ways derive economic value in a clear way. In addition, all of the economic outcomes presented are market-based quantifications or monetisation (for article references, see Appendix J).

Studying the environmental aspects in the articles (Fig. 14),

outcomes related to climate change are the most frequently occurring category, with quantified CO₂ reductions being the typical outcome, although landfill and methane reductions are also identified as sources of climate change benefits. Freshwater use reductions are the second most frequent category of the environmental outcomes. Additionally, the study found outcomes in the articles associated with all of the defined environmental categories, which could be explained by the frequent use of LCA as a research method.

Fig. 15, present the results regarding social outcomes in the analysed articles. The results show that not all categories were found in the studied material and that networking outcomes or benefits were the most widely occurring social outcome, followed by income and work. However, when examining these results in detail, social outcomes concerning networking effects are exclusively related to activities centred around the market producer institutional unit (such as a company or firm). Thus, the social benefit of networking can be considered more of an economic effect for a company than for individuals or society at large. Something similar can be observed regarding education, innovation and skills, as the knowledge benefits for individuals or society are not the focus of the articles. Rather, the outcomes are more or less directly connected to market producers and could be considered as an economic effect. Although there was one article referring to social equity and justice related to labour practices and decent work, no article identified outcomes related to gender equality, peace or political influence.

When studying the results by cross-referencing in Table 4, the results show that Material, by-products and waste is the most studied synergy category for economic and environmental outcomes and value. Energy synergies occur roughly in half the number of articles compared to

Table 4

Outcomes and symbiosis categories In this table outcomes are presented by row and symbiosis category by column. As several aspects in both row and column can appear in each article, neither rows nor columns should be summarised for totals. For totals see Figs. 12–15. The colour shading in the table ranges from red, indicating no occurrences in any articles, to green, indicating the maximum number of articles containing the combination of categories.

Outcomes (value and benefits)	Symbiosis category		
	Energy	Material, by-products and waste	Water
Market-based valuation	16	27	9
Nonmarket valuation	0	0	0
Climate change	28	40	15
Chemical pollution and hazardous waste	8	11	7
Rate of biodiversity loss	4	5	3
Acidification	8	10	6
Land-system change	3	5	4
Biogeochemical flows	2	3	2
Ozone depletion	1	2	2
Freshwater use	16	18	13
Atmospheric aerosol loading	5	5	3
Access to water and sanitation	1	2	2
Food and food supply	2	5	2
Health	4	5	1
Education, innovation and skills	4	5	1
Income and work	8	9	2
Gender equality	0	0	0
Political voice	0	0	0
Networks	8	12	1
Social equity	1	1	0
Housing	3	3	0
Energy access	2	2	0
Justice	1	1	0
Peace	0	0	0

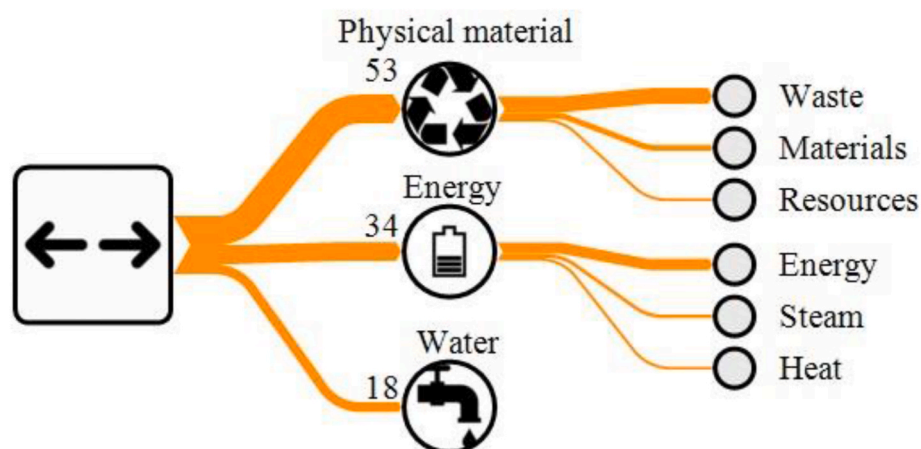


Fig. 13. The figure shows how many articles study the three symbiosis categories. 53 includes physical material synergies, 34 includes energy and 18 includes water synergies. Next, each symbiosis category is broken down into inductive categories with the most frequently used terms or words specific to the synergy category. For example, the most commonly occurring term for physical material synergy is waste synergies.

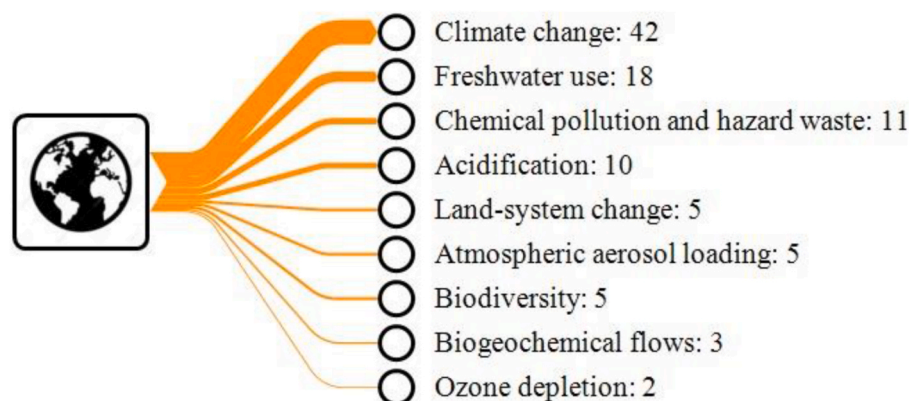


Fig. 14. The figure shows how many articles contain environmental outcomes according to the defined categories in this paper.

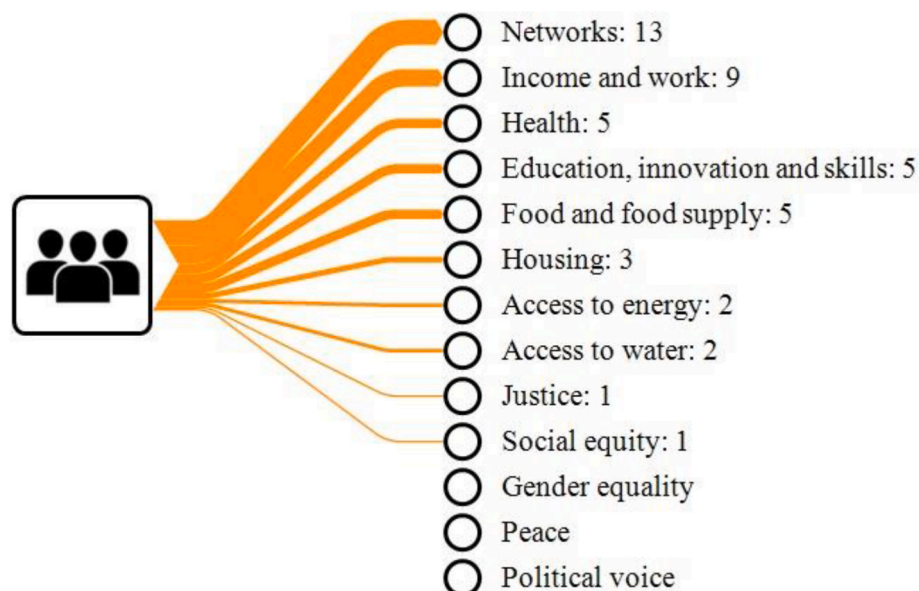


Fig. 15. The figure shows the number of articles that contain social outcomes as defined in this paper.

physical material synergies. Social outcomes are much less explored in the articles; however, network effects are the dominating outcome. Moreover, income and work outcomes occur in combination with all synergy categories. It should, however, be noted that the lack of particular outcomes cannot be connected to any symbiosis category specifically, because the paper is not studying whether the type of symbiosis category influences the presence of certain outcomes and value. This would be a task for future research. Thus, the paper is only studying the presence of the categories in the articles, not the reasons behind the presence. As the articles often contain more than one symbiosis category and the outcomes are often aggregated, and not linked to a specific synergy, thus it is hard to find clear patterns. Instead, the main takeaway from these results is that the attention received by the different synergy categories does vary in the articles, with material and energy-related synergies being the most studied symbiosis categories and (industrial) wastewater synergies frequently also appearing. Furthermore, to a large extent, the focus seems to be concentrated around certain outcomes and types of value in the articles, something that perhaps may affect the richness and diversity of industrial symbiosis research.

Finally, this section presents and analyses the results regarding the temporal distance in the articles. Fig. 16 shows that the most frequently used time horizon for the analysis is between one and two years, and only two articles include timeframes longer than 21 years, with the longest time horizon being 33 years (see Appendix M for references). Information regarding time horizons used in the articles was generally hard to discern, even in the LCA studies. Furthermore, some articles used data from other studies and did not provide detailed information besides referencing the source.

5. Discussion

Industrial symbiosis has been identified as a way for manufacturing and industrial production to break with the traditional linear production model and include multiple and complex relationships with various actors and stakeholders (e.g. private and public firms, other social actors and government) [52]. Even though there are multiple expected benefits in an industrial symbiosis collaboration, there are also difficulties within the concept. Amongst these difficulties are the many definitions [53] and the wide range of expected benefits, ranging from environmental benefits and monetary gains to positive social outcomes [54]. This makes a precise and comprehensive assessment challenging. Several informative reviews explore and analyse how to evaluate an industrial symbiosis [1,7,53,55]. However, a comprehensible analytical

framework is still lacking, that can situate a variety of industrial symbiosis outcomes and types of value (quantitative and qualitative) for the whole economy. This kind of framework will be essential to the understanding of how sustainable development is linked to economic growth and how actors in industrial symbiosis (institutional units) are linked to market and nonmarket effects. A striking example of the need for such a framework is when evaluating investments according to the EU's taxonomy for sustainable activities [56], and its regulatory framework to facilitate sustainable investment [57]. Which will govern future sustainable investments in Europe. Furthermore, even though environmental aspects are commonly studied in industrial symbiosis literature, addressing climate change will require considerable further attention. Thus, developing methods and procuring new data are vital in the fight against climate change and transitioning to a sustainable society. For example, machine learning could be a powerful tool [58] examining the more unexplored areas pointed out in this study.

Another topic for discussion is the inherent assumption that industrial synergies invariably bring about advantageous and positive outcomes. This assumption is however very unlikely as developing an interconnected synergetic industrial system involves managing conflicting interests and trade-offs leading to both positive and negative outcomes. Thus, creating an industrial synergy or designing an industrial symbiosis research approach, can place great informational burdens on practitioners and analysts to include all relevant actors and effects. By applying the analytical framework, this study has shown that outcomes in industrial symbiosis research are often based on similar measurements, and that actors and outcomes often are of the same kind regardless of research approach or choice of method. Striking examples of this is that economic outcomes in the studied articles are generally equated with market value and that benefits are credited to actors in the private sector. It is likely that different industrial symbiosis collaborations will have different sets of winners and losers when it comes to benefits or costs. This issue makes it important to understand what outcomes constitute real effects, providing gains for the whole of society, and what are merely transfers of resources between actors. The application of the framework provides a base for including a broader, but also, specific set of effects and outcomes (economic, environmental and social), including a diverse set of clearly defined actors (institutional units). Used consistently, the framework can average out costs and benefits across institutional units, so that each unit is more likely to realize net positive outcomes from a full set of industrial symbiosis applications. An example of this could be to distribute benefits and costs between actors based on distributional goals in society. This may in turn incentivise actors from across the whole society, to engage in industrial

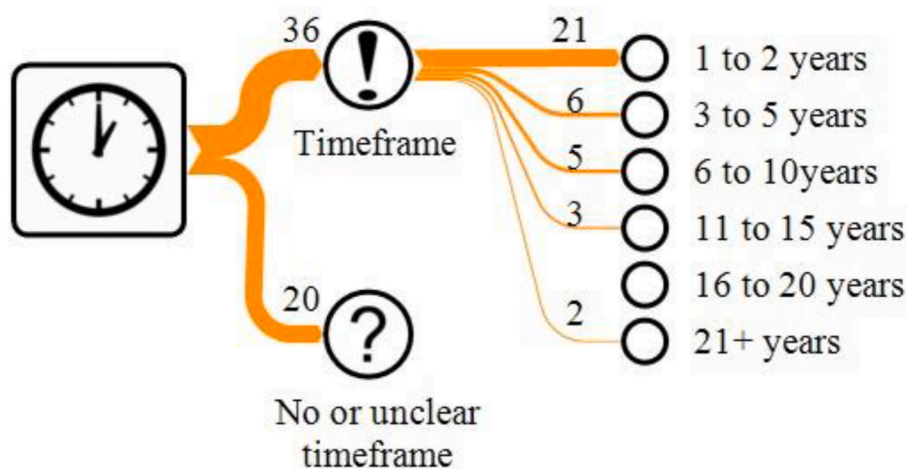


Fig. 16. The figure presents the distribution of the identified time horizons (temporal distance) in the studied material. Information regarding time horizons was found in 36 of the 56 articles. The most frequently used time horizons in the studied material were one to two years and the two longest time horizons were 23 years and 33 years.

symbiosis collaborations and share the costs.

It can also incorporate any available indicator or measurement, including nonmarket valuation and has the capacity to differentiate between institutional units and suitable valuation methods. This will greatly support the ability to broaden research in industrial symbiosis and strengthen the procedure of evaluating outcomes.

By breaking down current industrial symbiosis research into clear and detailed categories the results show that, regardless of method, the outcomes and value shown in previous research are rather homogenic in the sense that the articles study more or less the same things. Economic and environmental aspects are relatively well studied compared to social aspects – a finding also shown in previous industrial symbiosis literature [1,7,9].

The findings show that a variety of methodological approaches, both qualitative and quantitative, are applied in the articles investigating industrial symbiosis. The results are in line with previous research in industrial symbiosis and the circular economy. For example, Merli, Preziosi, and Acampora [59] present a review of the academic approaches to the circular economy literature, while Neves et al. [1] present the main lines in industrial symbiosis research. Interviews and LCA are especially frequent in the material, where the interview method is also the method most used in combination with other methods, both as the main research method but also as a form of data collection approach. The frequent use of LCA is also supported by previous studies [60].

The institutional units predominantly studied in the articles are market producers in the form of companies, firms or manufacturing industries and plants. This is also in line with previous research [7,61]. However, in this paper these findings are ascribed to the general focus on private actors and firms collaborating in industrial symbiosis. It is also found that the nonmarket producers included in the analysis (government and households) rarely participate in a capacity other than as facilitators or as a support function for forming synergies. Exceptions to this include articles studying how taxes and subsidies impact industrial symbiosis collaborations. But then again, the outcomes are still connected to the market producing institutional units.

Considering the three types of symbiosis categories defined in this paper, physical materials are the most studied synergy category, although all three categories frequently occur simultaneously in the studied industrial symbiosis research. The results are largely in line with other studies of what exchanges are considered [6,7,53,62]. Furthermore, the analysis did not find any clear occurrences of other types of non-product resource sharing, as exemplified in Lombardi and Laybourn [43].

There are many occurrences of economic outcomes in the studied articles, much in line with previous literature [9,63]. But the expected or actual economic outcomes occur as either purely descriptive, with more or less implicit value, or as market-based value. The observed pattern from analysing the material is: if there is a market price and clear physical unit, then there is measured and monetised value, or other forms of quantified outcomes. When market-based valuation is not possible, the economic outcomes and value are more or less assumed. Also, as time horizons are usually between one and two years, and it is not common practise in the articles to discount the resulting cash flows, it becomes hard to compare or evaluate the results among the various cases or between points in time.

Environmental aspects are common in the studied articles, and all of the categories occur at least once. However, a few categories received considerably more attention, e.g. GHG emissions and freshwater use, compared to the other environmental categories. This is also in line with previous research, as environmental outcomes are at the heart of the industrial symbiosis concept [1,59,64]. However, the way in which aggregation of outcomes are performed vary greatly in the literature, thus there is need for careful interpretations regarding the magnitude of the impacts [65].

Several of the identified social outcomes and types of value could be considered as transfers of benefits rather than social net benefits or

value. For example, income and work outcomes, which in economic theory are economic effects and not value, are more or less described as economic activities that benefit market producers. Also, the outcomes including learning, knowledge, innovation and skills type are not detailed enough to be properly organised, assessed or traced to any meaningful economic activity category. For example, some of the outcomes found in the articles could be considered as investments in human capital, but the level of details and necessary methodological considerations are lacking. The market-oriented research also focuses more on policy promoting industrial symbiosis [54,66] and the collaboration mechanisms rather than the social effects in society at large. The body of literature studying societal mechanisms related to collaboration, trust, peace and democracy can serve as inspiration for future industrial symbiosis research.

The study is not without limitations. First of all, the results stem from a finite and limited sample covering the current industrial symbiosis literature and future applications of the framework should include related research fields such as circular economy (CE) and process integration (PI) literature etc. Preferably, each research field should be analysed separately to enable meaningful comparisons. Also, there is no claim that the results are generalisable enough to explain all situations. However, by clearly defining the research questions, considering only existing and hypothetical industrial symbiosis cases, the analysis becomes transparent, precise and highly informative. Also, the content analysis methodology is often considered devoid of a theoretical base for the analysis, but this paper use a largely deductive coding frame, with the analysis based on clear theoretical perceptions and concepts. Basing the coding frame on well-established theories also supports the process of reducing the complex issues for analysis. An unavoidable disadvantage is loss of context in the studied articles, due to the fact that not all the details surrounding the research are presented in the articles. And thus, a third-party analyst will not be able to obtain the full picture from the texts. However, these limitations are minor as clearly defined aspects are studied through explicit and firmly established concepts, not aiming for a total description of everything in the articles.

Nevertheless, it is the authors belief that the framework presented in this paper will point to knowledge gaps and open up for new innovative research. By having a clearer picture of all the elements involved in a synergy, it becomes easier to incorporate novel ideas as well as developing already available ones.

6. Conclusion

According to the results from the review, a typical case of industrial symbiosis research would be either a qualitative study or an LCA – studying energy and physical material flows, either within or between companies during a year – where the outcomes are measured in reduced CO₂ emissions, reduced water usage and with market-based economic effects for the companies involved. Moreover, when evaluating industrial symbiosis synergies, many of the framework categories can be hard to clearly identify in the literature since avoiding interpreting is vital for a content analysis. Furthermore, the distinction between real or potential cases and synergies are often obscure or non-existent, leading to limited transparency. Therefore, there is need for future studies to be clear on whether the studied synergies are real or hypothetical.

Thus, there are two important pathways for future research in industrial symbiosis. On the one hand, revisiting previous research using well defined categories specifying all components in the symbiosis will extend the knowledge from already available methods and studies, while also increasing research transparency. On the other hand, expanding knowledge by broadening the scope of industrial symbiosis research by including costs, more of environmental and social outcomes. For example, future research could fruitfully explore collaborative outcomes related to peace, gender equality and political voice and how it can impact central social issues. Likewise, nonmarket producers involved in industrial symbiosis deserve more attention than is currently

given. The findings also suggest that existing evaluation methodologies need a more rigorous organising structure in order to fixate the analysis and explain the causal chain of outcomes and value. Thus, there is a need for an analytical framework that can identify and define institutional units from an economic perspective, and link and relate the specific outcomes to economic activities in a suitable manner. In this regard, the ability to include and compare various effects, both within and across outcome categories, makes the framework a suitable evaluation tool when it comes to ranking different synergy options or symbiosis projects. Furthermore, the total lack of nonmarket value in the research points to a potentially interesting area of future research. In this regard, the concept of total economic value combined with research covering social outcomes would greatly increase the deficient knowledge of social effects stemming from the practice of industrial symbiosis. For example, it would be informative to study what impacts industrial symbiosis collaborations have on social justice, political voice and gender equality aspects in developing nations. Also, there is a need for further development of stress tests and evaluation methods that incorporate clear timeframes, and that also include longer time horizons, in order to explore possible scenarios for future development while limiting myopic tendencies and path dependency.

Credit author statement

Wadström. C: Conceptualization, Methodology, Formal analysis, Writing original draft, review & editing. **Johansson. M:** Validation, Supervision & Funding acquisition. **Wallén. M:** Validation & Supervision.

Declaration of competing interest

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

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Appendix A to M. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.rser.2021.111526>.

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