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# Synergies and trade-offs between ecological and productivity-enhancing measures in industrial production – a systematic review

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## Abstract

**Purpose** – Improving productivity and efficiency has always been crucial for industrial companies to remain competitive. In recent years, the topic of environmental impact has become increasingly important. Published research indicates that environmental and economic goals can enforce or rival each other. However, few papers have been published that address the interaction and integration of these two goals.

**Design/methodology/approach** – In this paper, we identify both, synergies and trade-offs based on a systematic review incorporating 66 publications issued between 1992 and 2021. We analyze, quantify and cluster examples of conjunctions of ecological and economic measures and thereby develop a framework for the combined improvement of performance and environmental compatibility.

**Findings** – Our findings indicate an increased significance of a combined consideration of these two dimensions of sustainability. We found that cases where enforcing synergies between economic and ecological effects were identified are by far more frequent than reports on trade-offs. For the individual categories, cost savings are uniformly considered as the most important economic aspect while, energy savings appear to be marginally more relevant than waste reduction in terms of environmental aspects.

**Originality/value** – No previous literature review provides a comparable graphical treatment of synergies and trade-offs between cost savings and ecological effects. For the first time, identified measures were classified in a 3 × 3 table considering type and principle.

**Keywords** Eco-efficiency, Environmental sustainability, Sustainable manufacturing, Productivity

**Paper type** Research paper

## 1. Introduction

More than 30 years ago, the so-called Brundtland Report concluded that industry is both a cause of environmental problems and an important enabler for change through economic growth. Even then the need to reconcile environmental protection and economic growth was recognized as possible and desirable (World Commission on Environment and Development, 1987).

Meanwhile, the manufacturing industry must not only meet customer demand efficiently, but also adhere to the social and environmental requirements of a wider set of stakeholders. Therefore, companies' strategy should simultaneously consider and balance financial, ecological and social goals. Spreckley (1981) was presumably the first who criticized that the

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appraisal of industrial and commercial performance ignores social and environmental costs of the production process. This led to the well-established triple bottom line perspective of sustainability: economic prosperity, environmental quality and social justice (Elkington, 1994, 1997, Parkin *et al.*, 2003). The shear zone between the economic and environmental agendas is called eco-efficiency (Elkington, 1997) and has been examined in a more differentiated manner over time (Kleine and von Hauff, 2009; McDonough and Braungart, 2002a) as shown in Figure 1.

In literature one can often find the blanket assertion that improving the company's environmental performance is linked to long-term cost reduction (e.g. Florida, 1996; Despeisse *et al.*, 2012; Hart, 1995). Higher profits of a more ecological production could be attributed to higher productivity, but they can just as well be the result of avoided penalties (Tan *et al.*, 2022) or increased sales due to a better corporate image (Martín-de Castro, 2021). Baines *et al.* (2012) have already shown in a detailed review that a higher resource productivity can offset the cost of environmental improvements. However, this evaluation was conducted a decade ago and should now be repeated to include state-of-the-art measures to increase productivity and/or environmental performance.

According to Baah *et al.* (2021) environmentally sensitive production processes have a negative influence on financial performance. It is also conceivable that ecological aspects (and related monetary and non-monetary goals) outweigh the exploitation of all productivity potentials.

The target of this paper is to screen publications with cases where quantitative results of symbiosis, synergies, conflicts or rivalries between ecological and productivity-enhancing actions have been reported. Similar to Abolhassani *et al.* (2018) we use the term "productivity enhancement" synonym to productivity improvement and other expressions for increased production efficiency or production performance. The examples should also fit into a descriptive framework which consists out of a starting condition, followed by an event with one or more actions and resulting in an outcome where the impact caused by the implementation is evaluated (used in a similar way by Baldassarre *et al.*, 2019). Afterwards, statistical characteristics as well as correlations and patterns are recognized and revealed.

In section 2, relevant terms are described since a clarification is needed for the clustering of the result of the literature review. Section 3 is about the methodology, design and search strategy of the literature review. The listing and examination of the data from 66 publications

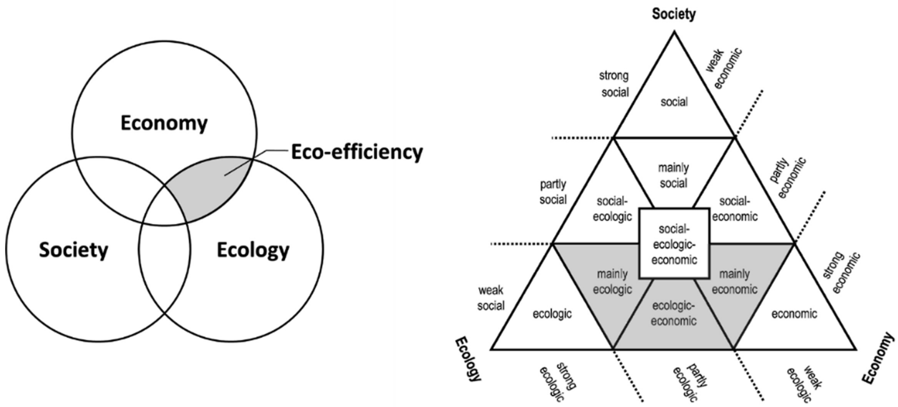



**Figure 1.**
Dimensions of sustainability and integrative sustainability triangle

**Source(s):** Parkin *et al*. (2003), Kleine and von Hauff (2009) followed by typecasting are subject of Section 4. Finally, Section 5 states the conclusion and future research directions.

## 2. Background

Increasing efficiency in production has always been in focus; prominent examples around the middle of the 18th century are the concept of division of labor and the beginning of the Industrial Revolution. In the past decades, ecological sustainability has become increasingly important in addition to pure business activities: stringent environmental policies and regulations, natural resource preservation and the public image affect the competitive advantage of a company (Despeisse *et al.*, 2012). Back in the 1980 and 90s, environmentally conscious thinking and acting was recognized and researched as an unavoidable success factor for companies (i.a. Hart, 1995).

A typical scenario where environmental protection and profitability are not compatible, are more ecological productions whose additional costs do not amortize (e.g. due to elasticity of demand). A vivid example is the dilemma of surface treatment mentioned in Luttropp and Karlsson (2001): just omitting coating would be more ecological due to the avoidance of harmful substances, but could have a negative impact on aesthetics and customer acceptance and in the end on sales and narrow profitability goals.

There are countless names for the various approaches and different possibilities for joining efficient industrial production with environmentalism. However, there is also no consistent terminological definition with strict distinctions. This complicates a literature review in that the search strategy cannot be narrowed to just a few keywords without running the risk of overlooking relevant publications. In their review in the field of "industrial sustainability", Smart *et al.* (2017) distilled 114 related keywords within multiple iterations and the final set of search strings still consisted of 90 keywords.

In general, it can be stated that terms that contain the word "sustainability" (e.g. sustainability manufacturing, industrial sustainability) consider all three dimensions mentioned in Section 1. Most publications also adhere to this concept (e.g. Paramanathan *et al.*, 2004; Smart *et al.*, 2017). In case of deviations, this is indicated by corresponding designation (e.g. environmental sustainability in Sarkis and Zhu, 2018).

Davis and Costa (1995) coined the term "environmentally conscious manufacturing"; it improves the environmental attributes of product manufacturing, ideally without sacrificing quality, cost or performance. The focus is on materials processing and manufacturing operation steps in order to reduce their environmental impact independently of the product. Smart *et al.* (2017) have decided to use the theme "material utilization and process optimization", which includes concepts like "sustainable manufacturing", "eco efficient processing" or "eco materials".

It is also Smart *et al.* (2017) who distinguish here between product and process/production. Of course, many environmental aspects such as the substitution of toxic materials by non-toxic ones, selection of suitable recyclates, source reduction and durability, reparability and dismantling of products are determined in the product development process. In this context, the terms "design for environment" (DfE, Davis and Costa, 1995) and "eco-design" (e.g. Luttropp and Lagerstedt, 2006) are commonly used, sometimes even as synonyms (e.g. Despeisse *et al.*, 2012). According to Graedel and Allenby (1995), DfE deals with products and processes before they are introduced and integrates environmental aspects over the entire lifespan of a product starting with the early stages of product design. It has become an important constraint for other considerations (e.g. design for manufacturing, design for (dis) assembly). Despeisse *et al.* (2012) criticized that DfE has a strong focus on products and encompass more than what a manufacturer has immediate control over. Anyway, an earlier integration of environmental thinking leads to better results in decreasing more effectively the environmental impacts of a product can be reduced (Keoleian and Menerey, 1994; Luttropp and Lagerstedt, 2006).

For this paper, the distinction between eco-efficiency and eco-effectiveness is of major importance. Eco-efficiency is about production processes with lower ecological impact. Most of the related strategies cover reduction of pollution (up to zero emissions), minimization of throughput and toxicity of materials used and energy-saving measures. Recycling capabilities only lead to downgraded material quality with limited usability and are not altering the linear progression of material flows (also known as downcycling; Ellen MacArthur Foundation, 2013). Eco-effectiveness is a concept where the production of goods goes beyond the reduction of negative consequences still existing in eco-efficiency. It is characterized by upcycling and a cradle-to-cradle design: products and processes are changed to be supportive for the environment (Burchart-Korol *et al.*, 2013). A self-sufficient closed-loop circulation of resources where waste from one component of the system represents input to another resembles a biological ecosystem and is seen as the highest level of ecological sustainability (Graedel, 1994; McDonough and Braungart, 2002b). According to Despeisse *et al.* (2012), few industries have considered their manufacturing as such ecosystems where material, energy and waste are used not only in an efficient way, but also in an effective way. By tracking process flows with a holistic view, compatible outputs and demands of processes can be identified. Ideally, virgin inputs can be substituted by wasteful or unwanted outputs generated elsewhere in the production system. Thus, for instance, efforts for imports and exports of resources are reduced or completely avoided, and thereby the environmental impacts are reduced while achieving economic savings. Baldassarre *et al.* (2019) summarizes industrial symbiosis as a synonym for a cooperative network of separate industries to exchange materials, energy, water and/or by-products. Related areas and aspects are circular economy and industrial ecology; Bruel *et al.* (2018) lists concepts, principles and tools both have in common, but also recommend to extend the focus by socioeconomic aspects.

An eco-effective transformation of resources can only be achieved via complete cyclicity. However, in industrial companies, individual components of the ecosystem (production processes, factories, etc.) are still examined in isolation. Thus, rather linear or quasicyclic flows are redesigned in the sense of (eco)efficiency (Graedel, 1994). At inter-enterprise level, the reduction of net resource input as well as pollutant and waste outputs remain essential. Nevertheless, a company that reuses its waste internally is more efficient than one which only focuses on the ratio of output over input of individual processes and fails to consider waste as a resource (Despeisse *et al.*, 2012); the optimized environmental impact through resource depletion is a pleasant side effect.

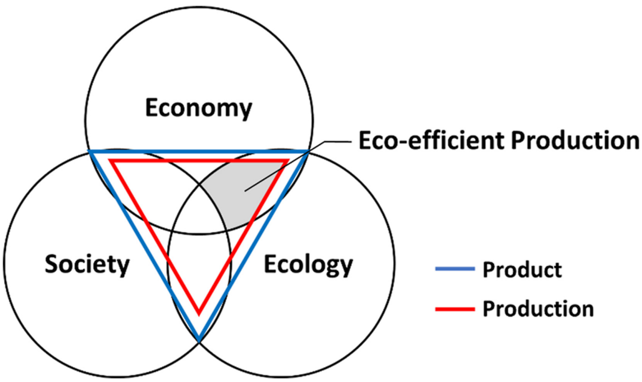
With all the above information, further topic narrowing is possible. The Venn diagram related to the triple bottom line (see Figure 1) is extended by two sets for product and production (illustrated by triangles, Figure 2). Since a product comprises more than just the processes of its creation, while production is meaningless without an associated product, the area of the product triangle is larger than that one for production and encloses it. The concentricity indicates, that for all dimensions and their shear zones, there are aspects that relate to the product but not to its fabrication; Sole exception is the center where all three agendas meet, as goods should only be considered fully sustainable when this also applies for their production. The production related economic/ecological shear zone marks the scope of this literature review and depicted by the grey area in Figure 2.

Consequently, product design and development, the utilization of the product and its end-of-life management are out of scope of this literature review. Also, the selection of (virgin) materials which are directly incorporated in the product (raw and auxiliary material, semi-finished from suppliers) are not considered. However, operating supplies and their environmental footprint as well as the utilization of by-products are relevant, as they are allocated to production. What also stays in focus are all kind of production systems. Viewed at the most abstract level, a production system converts resources into valuable output, typically via machining and assembly (Hitomi, 1996; Riggs, 1970). These systems are depending upon technology, equipment and industrial engineering techniques, and aiming at maximum productivity (Hitomi, 1996). Our further consideration includes individual processes and production steps, single production lines, factories, up to production networks (sometimes also called industrial parks). In individual cases, manufacturing technologies are also taken into account, as long as the increase in productivity has a significant environmental contribution (i.e. it exceeds the related energy savings) and vice versa.

## 3. Methodology

This systematic literature review is based on the PRISMA statement (preferred reporting items for systematic reviews and meta-analyses) developed by Moher *et al.* (2009). This guidance assists researchers in conducting reviews and reporting the results to ensure quality, clarity and transparency. For this purpose, the review process is subdivided into four phases: identification, screening, eligibility and finalizing the list of included studies.

The first phase is used to identify the objective of the research and the relevant keywords. Moher *et al.* (2009) as well as the latest update of the PRISMA statement (Page *et al.*, 2021) recommend to provide an explicit statement of all objectives or questions the review addresses. The corresponding checklist (latest version PRISMA, 2020) explicitly refers to the PICO framework. PICO is an acronym standing for population, intervention, comparison, outcome. This methodology was initially developed to test the effectiveness of interventions in medical practice (Richardson *et al.*, 1995) and is widely used in health research. Although the PICO framework has been used almost exclusively in evidence-based medicine so far, there are a few applications in other research areas recently (i.a. Baashar *et al.*, 2020; Burton *et al.*, 2018; Dong *et al.*, 2021). For this paper, a modified form of the PICO framework with its four criteria is used. In the present case, intervention (= ecological measures) and comparison (=productivity-enhancing measures) may but do not have to counteract each other since the targets of both measures can be combined. PICO stays suitable because it structures the literature search where we want to identify the relationship of two different measures (within industrial production (=population). The effects on the performance (e.g. improvements due to symbiosis and synergies, or deteriorations due to conflicts and rivalries) represent the outcome. A definition of the PICO criteria and their counterparts in this systematic review are listed in Table 1.




**Source(s):** Authors' own elaboration

**Figure 2.** Extended Venn diagram to express focus of the literature review

Each criterion is used to define a related search strings by identifying relevant keywords that serve as inclusion and exclusion criteria. This approach is in line with PRISMA (2020) according to which the PICO framework can be used to specify characteristics used to decide whether a publication is eligible for inclusion in the review or not.

Keywords for the first criterion "population" should ensure that search results deal exclusively with industrial production (second sector of the economy; economic activities that fall under section C in ISIC, 2008). Outside of the scope have been papers that refer to the primary sector of the economy where raw materials are extracted or produced such as mining and agriculture (including farming, logging, forestry and fishing). Also, construction industry and utility companies have been excluded since they do not fabricate conventional chattels. First queries showed that the keyword "production" resulted in many hits related to the agricultural sector; as a consequence, this term was replaced by more specific synonyms to narrow the search.

Second, the publications must explicitly refer to ecological measures (interventions) that directly affect the production. The explanations in Section 2 give an indication which key words are suitable for this search component and which are not. For example, the obvious word "sustainability" was not used because it also includes the society dimension (referring to social equity, health, safety, fairness, etc.). "Ecology" and "environment" were more appropriate words. Keywords which are referenced in the publications mentioned in Section 2 were adopted. Since each additional key word within a search string increases the number of hits, ambiguous and misleading terms such as "carbon" were not used. Due to the focus at the level of the production system rather than corporate governance, articles dealing with such topics as policy, carbon offsetting or renewable energies have been excluded in our paper.

For the search component about productivity-enhancing measures, the relevant keywords first had to be determined in a separate search step: in December 2021 the search string (productivity AND improvement AND industry AND production) was entered in Scopus database. This query led to 3,275 document results and was then limited to documents associated to the subareas "Engineering" (1,443 results), "Business, Management and Accounting" (511), "Material Science" (428) and "Chemical Engineering" (323). In Scopus it is possible to generate an overview of the keywords declared in the found documents and their frequency of occurrence. Among others, the terms "Lean Production" (134 results), "Lean Manufacturing" (83), "Industry 4.0" (54) and "Automation" (47) were noticeably often linked to the search results and consequently included in the search string. While management techniques (namely total quality management, just-in-time and lean production) have already

**Table 1.**
Criteria of the PICO framework with their definitions and corresponding search components of this review

| Criterion | Definition | Search component of the review |
|---|---|---|
| Population | Unit of interest to which intervention is/was applied (in medicine typically patient's problem) | Industrial production |
| Intervention | Treatment to which the population is exposed (in medicine a specific medication) | Measures to improve the environmental sustainability of production |
| Comparison | Comparator with no intervention or an alternative intervention or a counterfactual scenario (in medicine, e.g. a different therapy or placebo) | Measures to improve productivity of production |
| Outcome | Relevant results from the proposed intervention that can be reliably measured (in medicine, e.g. symptoms change and complications) | Effects on performance and competitiveness |

**Source(s):** Authors' own elaboration based on Collaboration for Environmental Evidence (2013) been incorporated by Baines *et al.* (2012) in a similar literature review, the topic of digitization constitutes a novelty.

Effects on performance and competitiveness (outcome) can be measured via common (financial) ratios such as market share or return on investment (ROI). Moreover, a company's reputation or customer satisfaction can be used as an indicator. Figge *et al.* (2002) but especially Geyi *et al.* (2020) summarized financial and operational performance measures which are partly adopted for this review.

The formulation and selection of keywords followed the principles stated in McGowan *et al.* (2016). Keywords created in this way were then combined into search strings by using Boolean operators and inserted as a search filter in the command lines of databases (Table 2). Where necessary for individual databases, the filters were adjusted.

These search filters were specified to be either in the title, abstract or keywords. Neither the year range nor the subject areas were specified in the search. There was no limitation to publication type but the search excluded those sources unavailable in the English language.

## 4. Results of literature review

The searches were run in January 2022 in Scopus and Web of Science databases and yielded 1,766 publications. In addition, there were 15 already known articles, some of them were even presented in Section 2. Altogether, 1,781 publications, including 340 duplicates, were identified. After screening the titles of all results from initial search, in a first iteration, only 546 potential publications remained. However, after abstract screening, 51 papers could be excluded.

Critically reading the identified 495 publications entirely in a second iteration, determined 43 sources relevant to this review. Together with additional 23 eligible papers found at the reference lists of the remaining publications (so-called backward snowballing; Wohlin, 2014), a total of 66 publications were included in the final analysis.

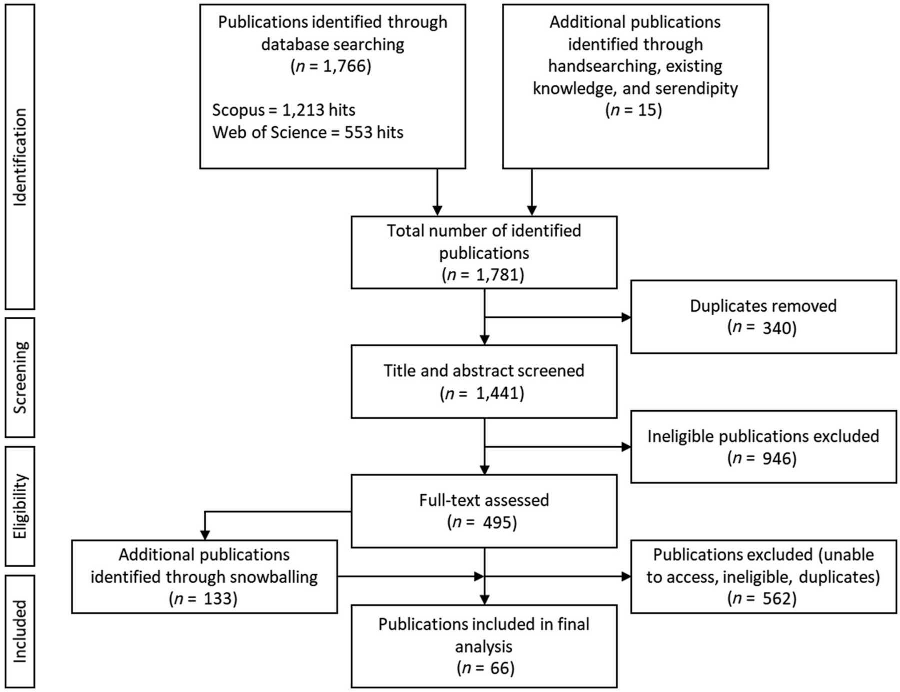
The above-mentioned phases of the review process are illustrated by the flow diagram in Figure 3.

As stated above, empirical cases providing examples and results of ecological and productivity-increasing measures are the main criteria for a publication to be considered for the final analysis. In exceptional cases, theoretical work like simulations or mathematical or

| Search component | Search string |
|---|---|
| Industrial production | Manufacturing OR assembly OR fabrication<br>AND |
| Measures to improve the environmental sustainability | "environmentally conscious manufacturing" OR "design for sustainability" OR ecodesign OR "design for the environment" OR greenhouse OR emission* OR "carbon footprint*" OR "environmental footprint" OR "circular economy" OR clean* OR ecolog* OR environmental OR "life cycle assessment" OR decarbonization<br>AND |
| Measures to improve productivity | productivity OR lean OR "industrial economics" OR "industry 4.0" OR agile OR automation OR digitalization OR "lead time reduction" OR "technical efficiency" OR "cost reduction"<br>AND |
| Effects on performance and competitiveness | competitive* OR profit* OR revenue OR "return on investment" OR roi OR "return on capital employed" OR roce OR "market share" OR sales OR turnover OR "customer satisfaction" OR reputation |

**Source(s):** Authors' own elaboration

**Table 2.**
Search filter




**Source(s):** Authors' own elaboration based on Moher *et al.* (2009)

**Figure 3.**
Flow diagram summarizing yield of literature review

experimental results and conceptual papers were also included, but not interview and questionnaire-based research when providing qualitative results only. Since the focus is primarily on industrial production, publications relating to the complete supply chain or the product itself (esp. design, material, remanufacturing; as mentioned at the end of Section 2) were excluded as ineligible. The same applies to publications related to the energy sector (including biofuel production) and services. Articles referring to governmental aspects (e.g. Porter hypothesis, emission taxation, national pollution control) as well as economics (such as region- or country-based studies) are beyond the scope and were ignored.

The risk of bias was mainly assessed by examining the disclosure statements and sponsors of the publications. In this respect, it should be noted that nine publications (Buandra, 2019; Glick and Shareef, 2019; Jarrell, 1992; Parthasarathy *et al.*, 2005; Stoll *et al.*, 2008; Takada *et al.*, 2008; Tokawa *et al.*, 2001; Vargas and Scott, 2017; Yamazaki, 2017) are co-authored by company representatives. In three additional cases, cooperation with companies is at least noteworthy (Tiwari *et al.*, 2020; Yang and Feng, 2008; Zhu *et al.*, 2007). The majority of publications are peer-reviewed journal papers or part of conference proceedings; exceptions are Ndikumana (2019), Pampanelli *et al.* (2015) and Wills (2009). Nevertheless, the authors of this paper concluded that there are no reasons for the exclusion of specific sources. All authors agreed on the final selection of publications and cases.

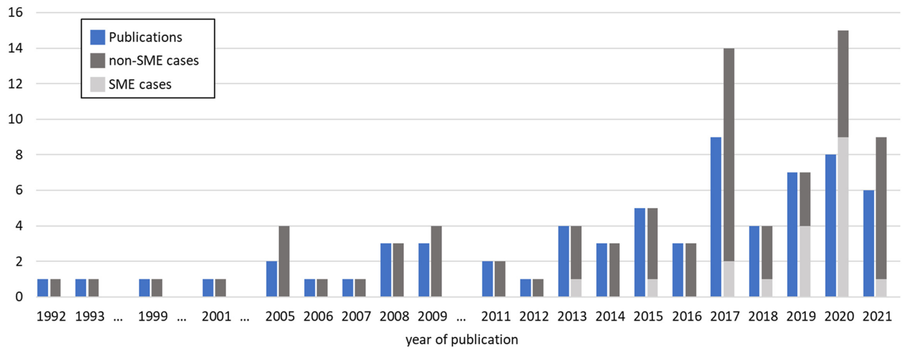
The high number of 66 relevant publications containing 84 cases from industry indicates the importance of the topic. A list of these cases together with a short description of measures and their economic and ecological effects can be found in the Appendix.

The company size is not documented for all of the sample cases, but at least 19 of them fall within the definition of a small and medium-sized enterprise (SME).

The selected body of literature comprises papers that have been published in a 30-year period ranging from 1992 to 2021. As Figure 4 shows, most of the sources (52) have been published in the more recent years, starting from 2011, with the highest number of works (8) published in 2017 and 2020, thus highlighting the growing interest devoted to the topic by scholars. Furthermore, the *Journal of Cleaner Production* dominates in terms of number of relevant studies, with 12 articles, followed by *Production Planning and Control* (5 papers), *Sustainability* (5) and *Clean Technologies and Environmental Policy* (3).

The company location is stated for 72 of the 84 cases. Figure 5 presents the information on the geographical distribution. Asian rank first by representing 38% of all analyzed cases led by India (10 cases) and China (7 cases). European countries are the source of 17 cases (24%), followed by North America (21%) and South America (16%). The lowest publication level was identified in Africa (2 cases) and Australia (no case in the final selection). With 14 cases, the USA are the country with the biggest contribution to this study.

Figure 6 portrays the industry-based distribution of the cases. The classification is in line with the divisions mentioned in ISIC (2008), 20 out of the 24 manufacturing-related divisions defined by ISIC are represented by the cases. Three cases do not allow conclusions about the industry. Since a company can operate in more than one single industry sector, the total number of assignments listed here is 88 and therefore still higher than the original number of cases. A considerable amount of research has been done in the manufacture of fabricated




**Source(s):** Authors' own elaboration

**Figure 4.** Temporal distribution of publications and cases used for further analysis

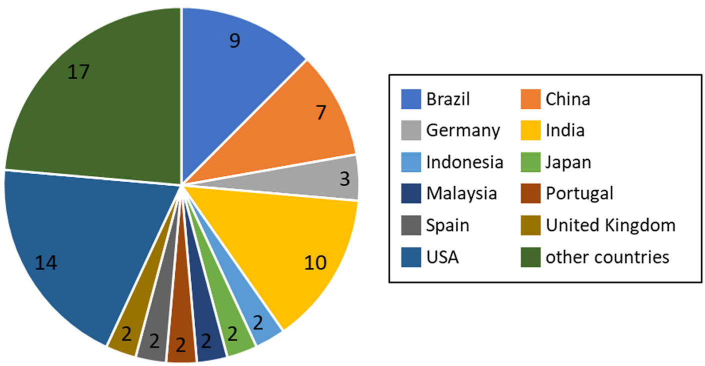



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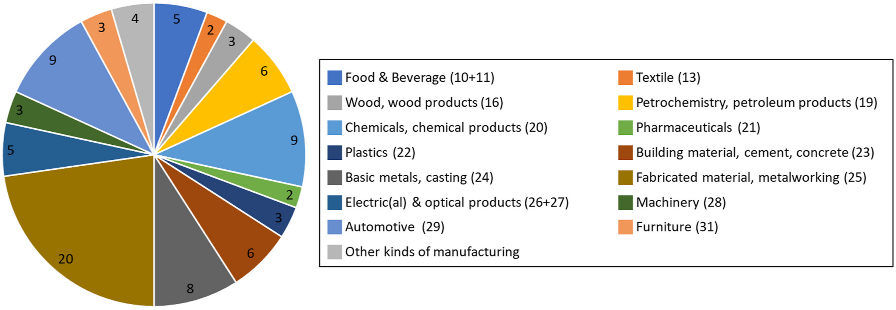
**Figure 5.** Geographical distribution of cases




**Note(s):** Identifier of ISIC division in brackets
**Source(s):** Authors' own elaboration

**Figure 6.**
Distribution of industry sectors assigned to cases

metal products (23%), manufacture of chemicals including chemical products and automotive industry (11% each).

43 of all cases refer to "costs" suggesting that cost savings are an important indicator for the economic success of a measure.

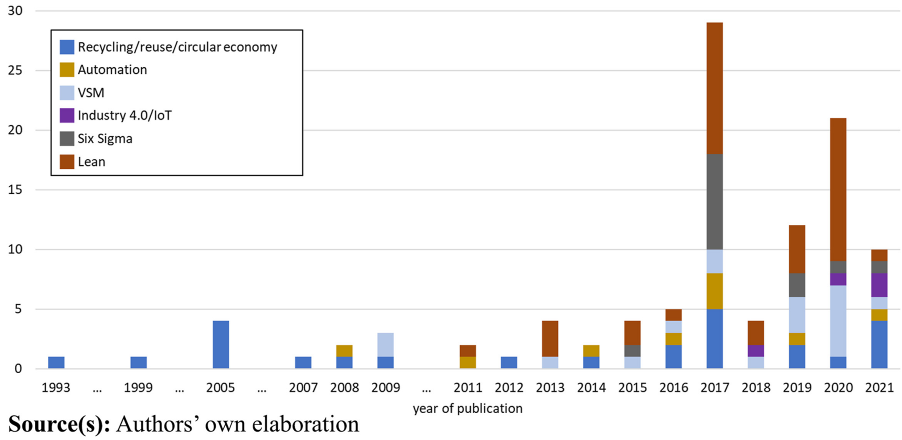
One of the central questions is what productivity-enhancing measures were used in the cases. Of particular interest is the spread of individual techniques and trends in their utilization. For this purpose, all cases were tagged in the further course of the analysis. These tags are "Recycling/reuse/circular economy", "Automation", "VSM", "Industry 4.0/IoT", "Six Sigma" and "Lean"; depending on the measure(s), it occurred that one case corresponded none or to several of the aforementioned tags (e.g. lean Six Sigma led to one tag for lean and another for Six Sigma, if applicable also a third tag for VSM when explicitly used in the case).

The first tag also covers publications dealing with industrial symbiosis or upcycling. Although VSM is a recognized method used as part of lean methodology as well as in Six Sigma, it is occasionally also used as an independent tool; hence it is treated as a separate category. The tag "Industry 4.0/IoT" is used for all measures which are associated with digitalization of production and sensors used there. The frequent references to Six Sigma caused this term to become a distinct tag as well. Originally designed to improve manufacturing quality, it also brings structure to process improvement through a define-measure-analyze-improve-control cycle (Pande *et al.*, 2000). Cases tagged with "Lean" typically implemented 5S workplace organization, continuous improvement process (also known as Kaizen), cellular manufacturing and/or just-in-time production.

As can be seen in Figure 7, there "Lean" is the most brought up measure and related to 43% of all cases. "Recycling/reuse/circular economy" is the second most widely used measure, thanks to the fact that it has been in focus since the 1990s and also remains relevant today. We found the theme of "Industry 4.0/IoT" represented only in 5% of the analyzed cases; those cases are from recent years and could be considered as new and promising tool.

Trends from the figure above are consistent with the findings from previous reviews (e.g. Cherrafi *et al.*, 2016; Chugani *et al.*, 2017) according to which lean production as well as Six Sigma (and of course combinations of both) are frequently used to achieve eco-efficiency. Direct search results and snowballing did not reveal fundamentally new techniques that were not already known when the search filter was designed. Only few detailed technical solutions (Huang *et al.*, 2017; Yamazaki, 2017; Khan *et al.*, 2021) as well as the use of artificial intelligence (Adeniji and Schoop, 2021) can be mentioned as extraordinary.

Since ecological aspects are multifaceted, clustering them is also a reasonable option here. It seems purposeful to loosely adhere to ISO 14044 - respectively Amrina and Yusof (2011) -



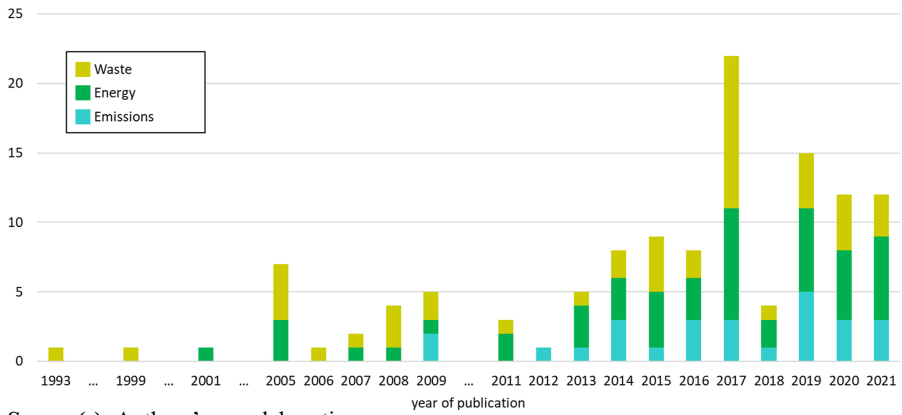

**Source(s):** Authors' own elaboration

**Figure 7.**
Temporal distribution of productivity-enhancing measures mentioned in cases

and distinguish between "Waste", "Energy" and "Emissions". The first tag covers solid and liquid waste and especially hazardous substances. "Energy" refers to the consumption of all kind energy sources and carriers such as fuels or electricity. Cases where air pollution are reported are attributed to "Emissions". Figure 8 illustrates the occurrence of these three ecological aspects over time; multiple tagging was possible.

Whereas waste and its reduction have been of consistent relevance constituting 53% of all cases, the issues of emissions and particularly energy have become much more important in recent years. Energy (efficiency) has a massive proportion of 57% of the cases considered. Although emissions to air and exhaust gases are comparatively seldom discussed (29% of all cases), an increase can be seen in the past few years. Whereas up to and including 2013 VOC were in focus when a case considered waste gases, since then GHG and above all $CO_2$ have been mentioned in almost all cases with reference to emissions.

The influence of ecological aspects on efficiency-enhancing measures in industrial production is emphasized in the introduction of most publications analyzed. Insights gained through the literature review suggest that improvements of the environmental performance




**Source(s):** Authors' own elaboration

**Figure 8.**
Temporal distribution of ecological aspects addressed in cases

of an industrial production have a positive impact on the productivity. For instance, Teng *et al.* (2014) found out that an environmental commitment proven by a certified environmental management system leads to benefits on economic performance. Especially Ben Ruben *et al.* (2017) states that initiatives to improve environmental performance must be aligned with traditional manufacturing strategies to improve metrics such as process efficiency, profitability or quality. Reliable figures are provided by Diaz-Elsayed *et al.* (2013): changes from the real state to the green state amount to 4.7% of the overall 10.8% savings in production costs.

For the vast majority of cases, the economic and ecological effects can be contrasted. Table 3 shows a rough rating of the extent of the effects. Improvements in the double-digit percentage range (for economic effects also payback periods shorter than five years) are considered substantial and represented by ++. A smaller improvement is subsequently designated as moderate (+). Mentioned improvements, which are given only in absolute values or without any values at all, are indicated by +? and commented. ○ is used if no changes have occurred. Declines are graded in the same way as improvements (– and -).

If both the economy dimension (i.e. positive economic effects) and the ecology dimension are improved by a measure, synergy can be assumed in the respective case. If an enhancement of one dimension is achieved at the expense of the other, the affected case is listed under trade-offs (these cases are grey shaded in Table 3).

To allow further conclusions the classification of measures is further refined. In the majority of cases, more than one measure was used.

The analysis of the cases shows that synergies between ecological and productivity-enhancing measures clearly outnumber conflicts and rivalries. Only ten cases of trade-offs between an increase in productivity or profitability and ecology could be identified; however, for some cases, external influences such as price increases or declines in sales volume may have affected the result. Clusters of trade-offs among specific industries or countries are not evident. This underpins substantial empirical evidence suggesting that productivity-enhancing measures can offset the cost of environmental improvements if these arise at all (Baines, 2012).

Baumer-Cardoso *et al.* (2020) and some articles referenced there suggest that while more frequent setups increase flexibility and achieve many positive ecological and economic effects, in the case listed, water consumption also increased. When comparing two technical solutions, Khan *et al.* (2021) evaluated and quantified a total set of 17 criteria. Lower manufacturing costs were associated with higher environmental impacts and vice versa. The lower-emission solution requires subsequent cleaning, which takes additional resources. A comparable case is described by Mangili and Prata (2020) where the lower-emission technology has a higher raw material consumption. Yue and You (2013) reported a deteriorated environmental impact per functional unit with increasing productivity. Another example of a trade-off is provided by Jayachandran *et al.* (2006): the most environmentally sustainable production process is associated with significantly higher and therefore unprofitable production costs. So, the technology was not used due to lack of commercial viability.

Furthermore, it is crucial which reference is considered: Leme *et al.* (2018) shows a case where eco-efficiency is higher even with an increased carbon footprint of the factory. After converting setup time into productive time, the machines will demand higher power levels because they are not in standby mode anymore. Consequently, the total energy consumption increased together with the production quota, but also the ratio of production time to carbon emission improved. Choudhary *et al.* (2019) also point to higher energy consumption due to increased production efficiency, but at the same time advises a correspondingly ecological procurement strategy.

| ID | Authors (year) | Effects Econ. | Ecol. | Comment | Applied measures (own interpretation) |
|---|---|---|---|---|---|
| 1 | Adeniji and Schoop (2021) | ++ | ++ | | A |
| 2 | Aguado *et al.* (2013) | ++ | ++ | | B, C |
| 3 | Baldassarre *et al.* (2019) | – | ++ | Project makes no profit so far | P |
| 4 | Baumer-Cardoso *et al.* (2020) | ++ | - | Disproportionate increase of water consumption | L, N |
| 5 | Belhadi *et al.* (2018) | ++ | ++ | | B, L |
| 6 | Ben Ruben *et al.* (2017) | ++ | ++ | | B, G, L |
| 7 | Buandra (2019) | ++ | ++ | | J, L, T |
| 8 | Chompu-inwai *et al.* (2015) | ++ | ++ | | F, M |
| 9 | Choudhary *et al.* (2019) | ++ | ++ | Despite net positive carbon savings, there is one process within the value stream where $CO_2$ emissions have worsened severely | O, R |
| 10 | Diaz-Elsayed *et al.* (2013) | + | + | | L |
| 11 | Fahad *et al.* (2017) | ++ | ++ | | B, J |
| 12 | Felsberger *et al.* (2020) | + | ++ | | A, M |
| 13 | Fu *et al.* (2017) | ++ | +? | No details about energy savings, pollution and waste reduction | F, I, L, M, Q |
| 14 | Gholami *et al.* (2021) | +? | ++ | No details about cost savings (declared as "significant" and "substantial") | F, G, M |
| 15 | Glick and Shareef (2019) | + | + | | M |
| 16 | Handoko *et al.* (2018) | ++ | ++ | | E |
| 17 | Huang *et al.* (2017) | ++ | + | | S |
| 18 | Iqbal *et al.* (2015) | +? | +? | No details about extent of productivity increase, energy savings and reduced emissions | I, M |
| 19 | Isasi-Sanchez *et al.* (2020) | ++ | ++ | | S |
| 20 | Jarrell (1992) | +? | ++ | Value of increased flexibility is unclear | E |
| 21 | Jayachandran *et al.* (2006) | – | ++ | Manufacturing costs are three times higher | D, E, S |
| 22 | Khan *et al.* (2021) | ++ | – | Results depend strongly on machine settings; there are some cases where synergies can be achieved | D, E, F, I |
| 23 | Kluczek (2017) | + | ++ | | D, E, F, H |
| 24 | Leme *et al.* (2018) | ++ | ++ | | L, T |
| 25 | Lucato *et al.* (2015) | +? | ++ | No details about economic effect of reduced cycle time and higher productivity | G, L, M, T |
| 26 | Mangili and Prata (2020) | ++ | + | Comparison of two technologies: the one claimed more sustainable scores worse in some aspects such as resource consumption | E, F |
| 27 | Marinelli *et al.* (2017) | ++ | +? | No details about ecological effect of recycling | P |

(*continued*)

**Table 3.**
Overview of economic and ecologic effects and applied measures at the identified cases

| ID | Authors (year) | Effects Econ. | Effects Ecol. | Comment | Applied measures (own interpretation) |
|---|---|---|---|---|---|
| 28 | Mashaei *et al.* (2011) | +? | ++ | No details about economic effect of changed throughput | M, T |
| 29 | Moreira *et al.* (2018) | ++ | ++ | | F, I, M, T |
| 30 | Nakajima (2015) | +? | ++ | No details about extent of increased profits | E |
| 31 | Ndikumana (2019) | ++ | ++ | | D, F, L |
| 32 | Păltan *et al.* (2019) | ++ | +? | No details about ecological effect of recycling | D, H, R |
| 33 | Pampanelli *et al.* (2015) | + | ++ | | L |
| 34 | Panjeshahi *et al.* (2009) | ++ | ++ | | E, H |
| 35 | Park and Park (2014) | ++ | +? | No reference value for resource savings | H |
| 36 | Parthasarathy *et al.* (2005) | ++ | ++ | | D, E, H |
| 37 | Pusavec and Kopac (2009) | ++ | +? | No details about ecological effect of replacing coolants | E, F, I |
| 38 | Roeckel *et al.* (1994) | ++ | ++ | | E, H |
| 39 | Rosen and Kishawy (2012) | ++ | ++ | | E, F, H |
| 40 | Scharf *et al.* (2021) | ++ | ++ | | A, D, E |
| 41 a-d | Sellitto *et al.* (2021) | ++ | +? | No reference value for ecological effect of recycling | P |
| 42 | Sgobba and Meskell (2021) | + | +? | No reference value for avoided emissions | H |
| 43 | Silva *et al.* (2020) | +? | ++ | No reference value for cost savings | L, T |
| 44 | Sobral *et al.* (2013) | +? | +? | Effects are not quantified | I, L, T |
| 45 | Stoll *et al.* (2008) | ++ | +? | No reference value for resource savings | D, E, F, I |
| 46 | Takada *et al.* (2008) | +? | +? | Effects are not quantified | E, I, R, T |
| 47 | Tamosiunas (2014) | ++ | ++ | | D, Q |
| 48 | Tang *et al.* (2016) | +? | +? | No reference value for increased profits; no values for emission decrease and resource savings | N |
| 49 | Tasdemir and Gazo (2019) | ++ | ++ | | B, G, K, L |
| 50 | Teng *et al.* (2020) | ++ | ++ | | L, M |
| 51a | Thanki and Thakkar (2020) | – | + | Case 1: waste reduction might be caused by lower sales or the like | L |
| 51b | | ++ | ○ | Case 2: waste stayed on same level | |
| 51c | | - | – | Case 3 | |
| 51d | | ++ | - | Case 4 | K, L |
| 51e | | + | ○ | Case 5: waste stayed on same level | L |
| 51f | | – | – | Case 6 | K, L |
| 51g | | - | - | Case 7 | L |
| 51h | | ++ | – | Case 8 | |
| 52 | Tiwari *et al.* (2020) | ++ | ++ | | G, L, T |
| 53 | Tokawa *et al.* (2001) | ++ | +? | No details about ecological effect of avoided coolants | E, F, I, T |
| 54a | Triebswetter and Hitchens (2005) | ++ | +? | No details about ecological effect of replacing resources for all mentioned cases | F, K, P |
| 54b | | + | | | |
| 54c | | + | | | |

**Table 3.** (*continued*)

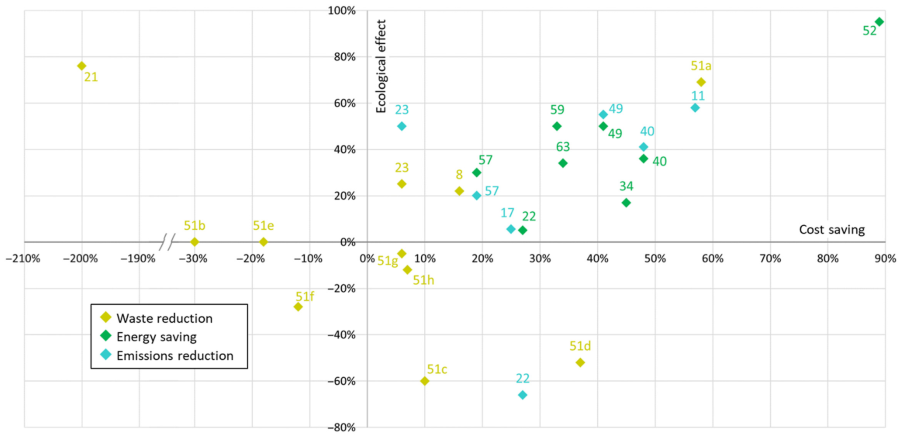
| ID | Authors (year) | Effects Econ. | Ecol. | Comment | Applied measures (own interpretation) |
|---|---|---|---|---|---|
| 55a | Vargas and Scott (2017) | ++ | +? | Case 1: No reference value for reduced gas consumption | C, E, G, J, L, Q, T |
| 55b | | +? | +? | Case 2: No details about extent of improved productivity; no reference value for reduced waste and water consumption | B, G |
| 55c | | +? | +? | Case 3: No details about reduced work hours (declared as "significant"); reference value for avoided waste | E, G, H |
| 55d | | ++ | ++ | Case 4 | G, H, K |
| 55e | | +? | +? | Case 5: No details about reduced downtime and product handling; no reference value for reduced waste | E, G, I |
| 55f | | +? | +? | Case 6: No details about reduced cycle time; no reference value for avoided waste | E, G, Q |
| 56 | Veltri *et al.* (1999) | ++ | ++ | | H |
| 57 | Vinodh *et al.* (2016) | ++ | ++ | | H, L, M, O |
| 58a | Wills (2009) | ++ | ++ | Case 1 | E, F, I |
| 58b | | ++ | +? | Case 2: No details reduced emissions and waste | |
| 59 | Yamazaki (2017) | ++ | ++ | | C, R |
| 60 | Yang and Feng (2008) | ++ | ++ | | P |
| 61 | Yue and You (2013) | ++ | + | For some solutions the environmental impact per unit produced increases sharply as productivity increases | N, O |
| 62 | Yun *et al.* (2014) | +? | ++ | No details about productivity increase | E |
| 63 | Zhang *et al.* (2018) | ++ | ++ | | E, H |
| 64 | Zhang *et al.* (2016) | ++ | +? | No reference value for resource savings | A |
| 65 | Zhi-dong *et al.* (2011) | + | ++ | | D, H |
| 66 | Zhu *et al.* (2007) | +? | ++ | No details about reduced costs Corporate group representing six cases | K, P |

**Note(s):** A: IoT, digitalization, artificial intelligence; B: changed layout (incl. rearranging processes/stations); C: retrofitting of material flow (addressing bottlenecks); D: retrofitting of equipment (energy-efficiency, low-pollution); E: retrofitting enabling new options/processes; F: change of used material, chemical composition, supplies; G: Six Sigma; H: internal recirculation and waste utilization (incl. cogeneration); I: reduced need of operating supplies; J: reduced transportation effort; K: sourcing/procurement; L: lean (5S, JIT, Kaizen, . . .); M: changed machine setting/calibration (incl. switch-off during non-activity); N: change of batch size; O: resource leveling; P: exchange of by-products (external); Q: automation; R: process integration; S: additive manufacturing; T: changes in time (idle time, shifts, cycle time, utilization)
**Source(s):** Authors' own elaboration

**Table 3.**

With respect to batch scheduling, Capón-García *et al.* (2011) and Dietz *et al.* (2006) refer to antagonist goals of maximizing profit and minimizing environmental impact. The qualitative analysis of Rothenberg *et al.* (2001) detected trade-offs between lean manufacturing techniques and emissions. Zhu *et al.* (2007) mention potential risks affecting productivity and worsening environmental burden.

Some cases provide data on cost savings percentage as well as relative improvements of the ecological aspects waste, energy and/or reduction. Thus, a more detailed juxtaposition of these cases is possible. Figure 9 illustrates 21 cases from 14 articles in a two-dimensional




**Source(s):** Authors' own elaboration

**Figure 9.**
Synergies and trade-offs between cost savings and ecological effects

Cartesian system; cost savings are plotted on the horizontal axis, and ecological effects on the vertical axis. Similar to Karvonen (2001), quadrant I contains the synergy cases or win-win situations where both effects complements, as an increase in one effect will lead to an improvement of the "opposite" one. Trade-off situations (lose-win or win-lose) arise when only one effect is enhanced but the other does not (quadrant III resp. quadrant IV).

The figure above suggests a correlation between energy savings and cost reduction respectively between emission reduction and cost reduction. It also shows that in three out of four cases, energy savings result in similarly high ($CO_2$) emission reductions.

Correlations can be assessed by using the statistical indicators Pearson correlation coefficient ($r$) as well as the coefficient of determination ($r^2$). The obtained Pearson correlation coefficient value of $r = 0.57$ indicates a moderate positive correlation between emission reduction and cost savings with a quite high goodness of fit ($r^2 = 0.32$). Energy savings and cost reductions show a weaker relationship ($r = 0.22$, $r^2 = 0.05$). Due to the outlier from Jayachandran *et al.*'s (2016) case, we calculated a negative correlation between cost savings and waste volumes ($r = -0.43$, $r^2 = 0.19$), which implies that the avoidance of waste is economically rather disadvantageous. By ignoring the extreme case, a positive correlation is obtained ($r = 0.29$, $r^2 = 0.08$).

It is important to note that the effects occurred in different time periods. In the case of Thanki and Thakkar (2020), this period is always two years. Once again, the extent to which effects can be explained by changes in sales and prices for raw material and energy remains largely ignored due to lack of data.

The resulting publications were also grouped into a 3 × 3 table to reveal the nexus between the type of measures and their guiding principles of impact. In the course of the literature review, it became obvious that the measures taken affected processes and/or the use of technology. As soon as new, different or additional equipment is used for optimization, it is a "technological measure". "Processual measures" are all corrective actions which change workflows and configurations, but use the existing production means. Of course, there are also measures that combine both types. The impacts of the measures can be subdivided into reduction, replacement or recycling in the broadest sense. Reduction means lower resource consumption (in some cases up to complete elimination); examples are reduced energy consumption, shortened idle times, avoided waste and eliminated work steps. Alternatively, hazardous substances, for instance, can be substituted by environmentally compatible solutions; in the case of such a replacement, resource consumption does not necessarily have to be reduced, at least from an ecological viewpoint. The principle "recycling" summarizes all kinds of waste treatment including upcycling, circular economy and industrial symbiosis. The assignment of publications within this framework can be seen in Table 4. It can be seen that the constellation "processual, reduce" is observed most frequently, which is due to the widespread use of the lean methodology (Figure 7).

Per se, there is no better or worse when it comes to the principles. But they can be understood as evolution steps: while reduction is almost synonymous with eco-efficiency, recycling rather aims at eco-effectiveness. The principle of replacement can be located in between, depending on whether it reduces or avoids environmental impacts. More recently, these principles are taken as hierarchical models (e.g. Kurdve and Bellgran, 2021; Lim *et al.*, 2022). In the end, zero-waste performance can be the aim or result of both lean and circular production (correlations were proven by Afum *et al.*, 2022).

When looking at Table 4, it is noticeable that reduction is very strongly associated with measures related to processes. This is not surprising, since lean principles are also designed to minimize all kind of waste and resource consumption, but they do not necessarily change the equipment or technology used. The situation is different for replacements, where modified production processes almost inevitably lead to a change of machines, tools and/or operating supplies. The distribution of publications related to recycling shows that both processes and the used technology are often adapted.

A further evaluation of the typecasted publications aims at a closer examination of the economic and ecological aspects considered. Table 5 shows which type of measure has an influence on what aspect (ordered by frequency of being mentioned).

Consistent with Figure 8, it can be seen that energy and waste are the crucial ecological aspects for almost all combinations of measure and principle. For measures focusing on "reduce", it seems that scheduling and timing is of particular importance.

The following tables are attempts to reveal further correlation and clusters of the typecasted measures, types of measures and principles of impacts. The numbers in parentheses indicate the frequency of occurrence.

By looking at the relative frequency, it can be observed in the case of individual measures (Table 6) that a changed layout reached, e.g. by rearranged stations or processes (B) can be considered to be a particularly eco-efficient measure. A double ++ rating was achieved in five out of six cases (83%). Also retrofitting of material flow (C), optimized transportation (J) and resource balancing (O) achieved this rating particularly frequently (67% each).

With regard to the types of measures (Table 7) and the absolute frequency, it can be stated that a combination of technological and processual measures results in the largest synergies. In the case of the principles of impact (Table 8), no robust statements can be made.

| Principle | Mainly technological | Mainly processual | Technological and processual |
|---|---|---|---|
| Reduce | [16], [22], [42], [45], [53], [55f] | [1], [4], [5], [7], [9], [11], [12], [14], [15], [18], [24], [25], [28], [29], [33], [39], [43], [48], [49], [50], [51a-h], [55b], [61], [64] | [2], [6], [10], [13], [31], [44], [46], [47], [52], [55a], [55c-e], [57] |
| Replace | [17], [19], [22], [23], [30], [37], [59], [62] | [8] | [20], [21], [26], [32], [40], [58a-b] |
| Recycle | [23], [34], [63], [65] | [41a-d], [54a-c] | [3], [27], [32], [35], [36], [38], [39], [55a-f], [56], [57], [60], [66] |

**Source(s):** Authors' own elaboration

**Table 4.** Typecasting of publications according to type of measure and principle of impact

**Table 5.** Frequently mentioned economic and ecological aspects of measures

| Principle | Mainly technological | Mainly processual | Technological and processual |
|---|---|---|---|
| Reduce | costs, payback period | (lead, cycle, queuing, setup, idle, etc.) time, costs, product quality, productivity (incl. OEE), profit | (cycle, lead) time, costs |
| | BOD/COD, $CO_2$, pollution in general | energy, $CO_2$, material consumption, water, operating supplies, solid waste | energy, operating supplies, water, waste, $CO_2$ |
| Replace | costs, (setup, lead, cycle) time, profit, productivity, product quality | no indication possible due to low number of cases | costs, flexibility |
| | energy, GHG, material consumption | | waste, energy, $CO_2$, material consumption |
| Recycle | production costs, capital costs, payback period | costs | costs, profit |
| | energy, operating supplies, (waste)water | energy, operating supplies | waste, energy, $CO_2$, water, waste water, COD |

**Note(s):** BOD: biochemical oxygen demand; COD: chemical oxygen demand; GHG: greenhouse gas; OEE: overall equipment effectiveness
**Source(s):** Authors' own elaboration

**Table 6.** Economic and ecological effects of typecasted measures

| Ecological effects \ Economic effects | ++ | + | +? | ○ | – | – – |
|---|---|---|---|---|---|---|
| ++ | A (2), B (5), C (2), D (4), E (8), F (5), G (4), H (8), I (2), J (2), K (2), L (9), M (4), O (2), P (1), Q (1), R (2), S (1), T (4) | A (1), D (2), E (1), F (1), H (2), L (1), M (1) | E (3), F (1), G (2), K (1), L (2), M (3), P (1), T (3) | | | D (1), E (1), P (1), S (1) |
| + | E (1), F (1), N (1), O (1), S (1) | L (1), M (1) | | | | L (1) |
| +? | A (1), C (1), D (2), E (5), F (6), G (1), H (2), I (5), J (1), K (1), L (2), M (1), P (6), Q (2), R (1), T (2) | F (2), H (1), K (2), P (2) | B (1), E (4), G (4), H (1), I (4), L (1), M (1), N (1), Q (1), R (1), T (2) | | | |
| ○ | L (1) | L (1) | | | | |
| – | L (2), K (1) | | | | L (1) | |
| – – | D (1), E (1), F (1), I (1), L (1) | | | | L (1) | L (1), K (1) |

**Source(s):** Authors' own elaboration

## 5. Conclusion and future research directions

This paper has its focus on the interaction and integration of environmental and economic goals. The systematic review found a total of 66 unique academic publications with

| Ecological effects | Economic effects ++ | + | +? | ○ | – | – – |
|---|---|---|---|---|---|---|
| ++ | Technological (5)<br>Processual (10)<br>Both (14) | Technological (2)<br>Processual (2) | Technological (2)<br>Processual (4)<br>Both (2) | | | Both (2) |
| + | Technological (1)<br>Processual (1)<br>Both (1) | Processual (1)<br>Both (1) | | | | Processual (1) |
| +? | Technological (3)<br>Processual (6)<br>Both (6) | Technological (3) | Processual (3)<br>Both (5) | | | |
| ○ | Processual (1) | Processual (1) | | | | |
| – | Processual (1) | Processual (1) | | | Processual (1) | |
| – – | Technological (1)<br>Processual (1) | | | | Processual (1) | Processual (1) |

**Source(s):** Authors' own elaboration

**Table 7.** Economic and ecological effects of types of measures

| Ecological effects | Economic effects ++ | + | +? | ○ | – | – – |
|---|---|---|---|---|---|---|
| ++ | Reduce (18)<br>Replace (5)<br>Recycle (9) | Reduce (2)<br>Replace (1)<br>Recycle (2) | Reduce (4)<br>Replace (3)<br>Recycle (1) | | | Replace (1)<br>Recycle (1) |
| + | Reduce (1)<br>Replace (2) | Reduce (2) | | | | Reduce (1) |
| +? | Reduce (5)<br>Replace (3)<br>Recycle (9) | Reduce (1) | Reduce (8)<br>Recycle (4) | | | |
| ○ | Reduce (1) | Reduce (1) | | | | |
| – | Reduce (1) | Reduce (1) | | | Reduce (1) | |
| – – | | | | | Reduce (1) | Reduce (1) |

**Source(s):** Authors' own elaboration

**Table 8.** Economic and ecological effects of principles of impact

statements and quantitative examples of conjunctions of measures in production systems. The considered cases have been published between 1992 and 2021. More than three-quarters of these have been produced over the last 10 years, reflecting the increased significance of considering dimensions of sustainability more holistic.

In most of the analyzed cases, it became evident that improvements of the environmental performance of an industrial production have also a positive impact on the productivity and vice versa. Only ten out of 84 cases reported conflicts and rivalries between productivity-enhancing measures and ecological aspects. This advocates environmentally conscious manufacturing from an economic viewpoint. There is little doubt that economic and environmental aspirations are already being addressed together. Rather, there is evidence for integrated approaches to achieve eco-efficient improvements.

Cost savings were identified as the most important economic aspect for an eco-efficient production as more than half of the cases deal with them. The ecological aspects can be divided roughly into energy, waste and emissions, whereby the latter have only recently gained importance. Energy savings appear to be marginally more relevant than waste reduction. For a total of 14 cases, correlations between cost savings and ecological effects could be represented graphically in a diagram.

This paper has also introduced a typecasting of measures via a $3 \times 3$ table for the first time. Measures can involve processes, technologies or both. These measures lead to reduced resource use, replacing previous means or recycling. It has been shown that measures aimed at reduction are primarily process-related and typically do not involve new technologies. Replacements, on the other hand, regularly require a modification of the used technology. To enable recycling or circular economy, often both processes and technologies are adapted. For academia, but especially for industry, our finding that the combination of technological and processual measures promotes eco-efficiency more than the isolated implementation of new technologies is highly meaningful. In relation to managerial implications, this study contributes to a better understanding on the potential effects of specific measures since data of various cases were examined and improvements up to the double-digit percentage range were found.

A next step toward understanding the synergistic relationship of ecological and productivity-enhancing measures is certainly to further develop the concept of the $3 \times 3$ table. In this way, potentials could be quantified and benchmarks for individual industries could be determined. This would enable a better comparison of heterogeneous cases. A potential result could be a process model to evaluate synergies and trade-offs and to support decision-making by using an empirically determined dataset. Moreover, established multi-criteria decision-making methods can be applied to quantitatively analyze interdependencies (e.g. by means of DEMATEL) or alternatives (e.g. PROMETHEE), possibly even in combination (Chowdhury and Paul, 2020). The final outcome might be a sector-specific guideline to identify the most eco-efficient measures. For this, more reference cases are needed that reflect the effects of individual measures, both in isolation and in combination with other measures.

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(The Appendix follows overleaf)

## Appendix

Appendix lists the output of the review, summarizes the measures applied in each case and states the observed effects. "Economic effects" include all changes (improving as well as worsening) that are related to operational performance and/or can be directly measured in monetary terms; this also includes chances in product quality. By "ecological effects" we refer to changes in environmental pollution and consumption of resources and energy.

| Authors (year) | Description of measures | Economic effects | Ecological effects |
|---|---|---|---|
| Adeniji and Schoop (2021) | Multi-objective optimization using digital process twins and artificial intelligence algorithms | Process queuing time and costs improved by 93%<br>Quality control pass rate increased by 5% | Total embodied energy reduced by 84%<br>Scrap rate reduced by 2% |
| Aguado *et al.* (2013) | Optimized, more linear layout to reduce intermediate stocks and movements<br>Additional and renewed machines to eliminate bottlenecks | Production capacity increased by 13%<br>Production time reduced by 70%<br>Reduced batch size (from 800 to 50 units) increased flexibility<br>Needed space reduced by 25% | Consumption of primary energy per unit reduced by 82%<br>Cumulative energy demand reduced by 78%<br>Environmental impact of manufacturing processes reduced by 22% |
| Baldassarre *et al.* (2019) | Collecting and distributing residual $CO_2$ and waste heat from industrial company into greenhouses | User save 50% energy costs<br>750 new jobs created<br>Project makes no profit so far | Avoids burning of 55m $m^3$ natural gas p.a.<br>135,000 t of $CO_2$ emissions are avoided p.a. |
| Baumer-Cardoso *et al.* (2020) | Implementation of lean principles, esp. Kanban and change of lot size | Lead time and work in process reduced by 83%<br>Processing time reduced by 14%<br>Production volume decreased by 32% | Consumption of raw material reduced by 13%<br>Energy consumption reduced by 14%, but water consumption increased by 206% |
| Belhadi *et al.* (2018) | Implementation of cellular manufacturing, continuous flow, supermarket pull system etc. | Production increased by 34%<br>Time efficiency increased by 27%<br>Changeover time reduced by 70%<br>Defect rate decreased by 17%<br>Total lead time reduced by 71%<br>Availability rate increased by 2% | Electrical energy consumed per product reduced by 45%<br>Water consumption per product reduced by 45%<br>Consumption for crude metals per product decreased by 29% |
| Ben Ruben *et al.* (2017) | Modification of layout and equipment via SMED, audits etc. | Cycle time reduced by 18%<br>Lead time reduced by 20%<br>Rejection costs reduced by 85% | Net power consumption reduced by 25%<br>Net water consumption reduced by 12%<br>Raw material required to manufacture reduced by 20% |

(*continued*)

**Table A1.**
Publications resulting from literature review and used in analysis

| Authors (year) | Description of measures | Economic effects | Ecological effects |
|---|---|---|---|
| Buandra (2019) | Production optimization through motion and time study lead to cycle operation from every third to every fourth shift | Reduced ladle utilization due to reduced number of activities from 66 to 55<br>Standard time reduced by 10% (from 39 to 35 min/ladle)<br>Operation hours are reduced by 21% for anode changing and by 11% for ladle transportation | Hydrogen fluoride emissions are reduced by 20.5% |
| Chompu-inwai *et al.* (2015) | Changes of material (wood type) and machine settings (blade angle, number of saw teeth) | System costs for cutting process decreased by 9%<br>Energy costs for cutting process decreased by 13%<br>Reduced material losses lead to cost savings of 16% | Material losses reduced by 22% |
| Choudhary *et al.* (2019) | Improving production via resource leveling, processes integration etc. | Reduced lead time by 63%<br>Production efficiency increased by 33%<br>Number of defects decreased by 57% | $CO_2$ emissions reduced by 77% (net savings of 967t of $CO_2$e per year) |
| Diaz-Elsayed *et al.* (2013) | Implementation of a combination of lean and green strategies (e.g. batch size reduction, use of energy-efficient engines) | "Green strategies" contributed 4.7% of the overall 10.8% savings in production costs compared to initial state | |
| Fahad *et al.* (2017) | Optimized layout reduces transportation effort and promotes maximum daylight usage | Costs for fuel und electricity decreased by 57% | Fuel consumed in material flow reduced by 62%<br>Lighting energy consumption reduced by 57%<br>$CO_2$ emissions reduced by 58% |
| Felsberger *et al.* (2020) | Algorithm to rearrange furnace charging | Throughput increased by 7% due to heating time optimization of furnaces | Energy consumption reduced by 10% due to reorganization of the pre-heating furnaces |
| Fu *et al.* (2017) | Modification of equipment (mold, pipeline, ventilation), redesign and automation of cleaning procedure, improved accessory mixing | Processing time reduced by 15%<br>Proportion of value-added process increased by 14%<br>Total cost saving of CNY 14.1 m p.a. (initial investment of CNY 6.8 m) | Material and energy savings, pollution and waste reduction |
| Gholami *et al.* (2021) | Optimized chemical composition decreased bleed-off volume without affecting quality and effectiveness of the process<br>Operating controller and sensors keep oven idle during non-activity | Significant cost savings | Consumption of chemicals reduced by 28%<br>Energy usage reduced by 21% |

(*continued*)

**Table A1.**

| Authors (year) | Description of measures | Economic effects | Ecological effects |
|---|---|---|---|
| Glick and Shareef (2019) | Optimization of electrostatic powder coat cure oven process | Process time reduced by 5% | Natural gas consumption reduced by 5% |
| Handoko *et al.* (2018) | Continuous improvement approach led to the installation of ammonia stripping equipment | Benefit of ammonia recovery of USD 3.4 m p.a<br>Total investment of USD 1.3 m (payback period of 5 months) | Pollution by ammonia decreased by 65%<br>BOD decreased by 3%<br>COD decreased by 10% |
| Huang *et al.* (2017) | In-house additive Manufacturing (T) | Downtime could be reduced by 70–80% compared to conventional manufacturing<br>Lead time reduced of 12–60%<br>Cost per part are 15–35% lower | Energy consumption could be reduced by 3–5%<br>GHG emissions could be reduced by 4–7% |
| Iqbal *et al.* (2015) | Fuzzy rule-based system leads to settings for the cutting parameters to optimize energy consumption, tool life and machining productivity | Increased feed rates reduce energy consumption; this ensures high productivity and reduced $CO_2$ emissions | |
| Isasi-Sanchez *et al.* (2020) | Potential of additive manufacturing to industry (T) | Profit might increase by 4% (equivalent to an increase of 15% over the margin with traditional manufacturing and distribution) | Estimated consumption of material reduced by 12%<br>Energy saving could reach 9% due to reduced transportation |
| Jarrell (1992) | New coating and laminating process | Increased flexibility | Resin usage reduced by 30% |
| Jayachandran *et al.* (2016) | Casting replaced by powder metallurgy process | Costs per part are three times higher than with casting<br>Increased tool life on the machining centers | Material waste per part reduced by 76% |
| Khan *et al.* (2021) | Combination of cryogenic and minimum quantity lubrication (compared to flood cooling) | Unit production cost of new technology are around 27% lower, but environmental costs are higher | Depending on the use case (esp. cutting speed), the $CO_2$ emissions per part produced are significantly higher<br>No need for cleaning, recycling and disposal with new technology |
| Kluczek (2017) | Replacing machines (e.g. from plasma to laser cutting, shot-blasting instead of sand blasting), installation of ventilation and filtering systems | Total production costs reduced by 6% | Cutting process: dust emissions reduced by 50%, material waste reduced by 25%<br>Blasting process: 258 t of sand are replaced by 4 t of steel shot<br>Capture of 1,465 kg of VOC p.a |
| Leme *et al.* (2018) | SMED with focus on $CO_2$ emissions | Idle and setup times reduced by up to 88% | Carbon footprint reduced by up to 81% |

**Table A1.**

*(continued)*

| Authors (year) | Description of measures | Economic effects | Ecological effects |
|---|---|---|---|
| Lucato *et al.* (2015) | Six Sigma extended by environmental variables such as consumption of electricity and chip generation of CNC lathes (T) | Increase the eco-efficiency to about 20% (and reduction of cycle time by 4%) | |
| Mangili and Prata (2020) | Comparison of butane-based and benzene-based maleic anhydride manufacturing technology<br>The butane route is considered to be 34% more eco-efficient | Butane process is 34% more profitable | Benzene process consumes less raw material (48%) and water (3%), and generates less wastewater (3%)<br>Butane process consumes 28% less energy and emits 43% less $CO_2$ |
| Marinelli *et al.* (2017) | Industrial symbiosis where non-marketable products and waste are used by livestock and other enterprises | Investment of EUR 0.4 m<br>Production company can sell waste at a 120% higher price | Production waste destined for disposal will become second raw material for processing companies |
| Mashaei *et al.* (2011) | Optimization of pallet system (T) | Number of pallets and conveyor velocity can be increased | Energy consumption reduced by 61% (for one specific configuration) |
| Moreira *et al.* (2018) | Calibration of machines, creation of quick wash program, implementation of new additives and activators | Cost savings of more than 30%<br>Average set-up time reduced by 26%, average OEE increased by 5%<br>Average MTTR improved by 21%, average availability (MTBF) increased in two of three studied equipment<br>Product quality improved by 5% | Isopropyl alcohol consumption reduced by 39%<br>Cleaning solvent consumption reduced by 3%<br>Additive consumption of fountain solution increased by 10% |
| Nakajima (2015) | Material flow cost accounting triggered change of manufacturing procedure | profits increased | Material losses of previously 32% was reduced by 80% |
| Ndikumana (2019) | Implementation of 5S, VSM and Kaizen<br>Elimination of production processes and usage of energy-efficient tools and equipment | Cost savings for electricity of ZAR 139k p.a<br>Reduction of rental costs of ZAR 293k p.a. since less space is needed<br>Savings of ZAR 313k since industrial gases are no longer needed for heat treatment process<br>Reduction of work-in-progress inventory improved cash flow by ZAR 166k<br>Lead time reduced by 1.5 days (from 6.4 to 5.9)<br>Yearly increase in total sales of 15,6% (ZAR 5.7 m) | Electricity consumption reduced by 32%<br>Reduction in the usage of industrial gas<br>Reduction in $CO_2$ emission by 97 t p.a |

(*continued*)

**Table A1.**

| Authors (year) | Description of measures | Economic effects | Ecological effects |
|---|---|---|---|
| Păltan *et al.* (2019) | Retrofitting the production lines with specific machines and merging or replacing production steps<br>Eliminating tight places with additional machines | Turnover increased by at least 22% due to additional capacities<br>Energy costs decreased by 19% | Generating electricity out of waste |
| Pampanelli *et al.* (2015) | Kaizen approach for improving environmental flows of mass and energy of manufacturing cells | Average cost reduction of 8% on cell level and 4.5% on value stream level<br>Productivity in the use of resources increased by 12% | Average resources consumption reduced by 35% |
| Panjeshahi *et al.* (2009) | Re-circulating cooling water system with cooling tower and heat-exchanger network interaction (T) | Total cost reduction of 45% compared to conventional system design (300% higher capital costs, but only 31% of operating costs) | 46% of make-up saving, 93% of blow-down water saving<br>Energy consumption reduced by 17% |
| Park and Park (2014) | Steam from waste incinerator is used instead of fossil fuel | Cost savings of over USD 4.1 m p.a<br>Portion of fuel costs of total operating costs decreased by up to 29% | $CO_2$ reduction of 45,500 t p.a<br>$SO_2$ reduction of 427 t p.a.<br>fuel consumption reduced by 18,850 t p.a. |
| Parthasarathy *et al.* (2005) | Shift from end-of-pipe treatment towards in-process waste reduction | Overall cost savings of USD 1m<br>Identification of saving potential of USD 3.3 m at installation cost of USD 6.3 m (payback period of 2 years)<br>Costs for program was USD 305k | Total waste reduced by >50%<br>Burning of 1.6 t p.a. of hazardous waste eliminated<br>Off-site treatment of 0.5 m t p.a. of organic waste avoided<br>Reduced need of fresh resources<br>Reduced generation of by-products (70% on unit level, 17% on site level)<br>Consumption of electricity reduced by 9.55 m kWh<br>Annual fresh water and waste water demand was reduced by 3.7 m $m^3$ and 1m $m^3$ respectively |
| Pusavec and Kopac (2009) | Conventional coolants such as air, oils and aqueous emulsions are replaced by cryogenic fluids (esp. liquid nitrogen) | Production costs reduced by up to 70% (depending on cutting speed)<br>Higher production rate (shorter cycle time)<br>Higher coolant costs, but lower machining cost and tool costs per part<br>No disposal costs and reduced power consumption | Hazardous oil-based emulsions are avoided<br>No residues or contamination of workpiece, chips etc. |

**Table A1.** *(continued)*

| Authors (year) | Description of measures | Economic effects | Ecological effects |
|---|---|---|---|
| Roeckel *et al.* (1994) | Introduction of a new step in the reduction process that involves recirculation of the pumping water and treating (i.a. screening, flocculation, centrifugation) resultant effluents | Productivity increased by 7%<br>Marginal profits are higher than the treatment cost for high technology plants, leading to a ROI of 53% after a 5-year period<br>Total investment of USD 2.2 m | Reduction of COD by 91.6% |
| Rosen and Kishawy (2012) | Implementation of measures to reduce VOC emissions (i.a. switching adhesive, recycle solvent) | Savings of CAD 349k p.a.<br>Payback period <2 years | Reduction of VOC emissions of 35% |
| Scharf *et al.* (2021) | Installation of modular gas-based burner technology<br>Novel process and plant concept using transportable melting and holding system<br>Process monitoring with sensors | Production costs decreased by 48% due to substitution of expensive electricity by cheap gas<br>Average cycle time is reduced by 5%<br>Better quality of products (tensile strength increases by 12%)<br>No cleaning and degassing of the melt by eliminating pouring processes<br>No overheating of the melt due to an improved transport process<br>More flexible production, because several alloys can be produced simultaneously approaching a lot size of one<br>Transportation can be performed by different vehicles | Energy demand to melt, transport and hold decreased by 36%<br>Consumed electricity decreased by 94% and gas by 32%<br>Accompanied $CO_2$ emissions decreased by 41% |

(*continued*)

**Table A1.**

| Authors (year) | Description of measures | Economic effects | Ecological effects |
|---|---|---|---|
| Sellitto *et al.* (2021) | Industrial symbiosis with eight dyadic or triadic relationships exchanging 300,000 t of by-products per year, comprising coal ash, mill scale, electric arc furnace dust, steam, zinc sludge, lead sludge and refractory lining leftover | *Steelmaking*<br>Operational costs reduced by 30%<br>Elimination of disposal costs<br>Cost reduction in purchases because refractory manufacturer accepts returns as part of the payment in sales<br>*Cement manufacturing*<br>Cost reduction due to recycling of by-products<br>Substantial reduction in manufacturing cost due to fly ash transfer from neighboring power plant<br>Ability to produce pozzolanic cement as an additional product | *Steelmaking*<br>Transfer of mill scale to cement manufacturer (safe destination for hazardous waste)<br>*Refractory liner manufacturer*<br>1 t of recycled waste preserves 3 t of magnesite ore and 1 l of fuel oil (avoids 700 kg of $CO_2$ emissions)<br>Leftovers from manufacturing process route as raw material to concrete artifacts manufacturing and road paving |
| Sgobba and Meskell (2021) | Evaluation of an on-site cogeneration system (T) | Expected payback period of 6 years | $CO_2$ emissions avoided in the first year are estimated to be 2,500 t |
| Silva *et al.* (2020) | Implementation of lean principles such as Kaizen, Jidoka and TPM | 33% reduction of cycle time (on average) leading to savings of EUR 124/month of energy costs<br>Savings of EUR1,000/months due to scrap reduction<br>Percentage of rework fell from 15 to 4% (now 0.5 h per worker and day instead of 1.5; saving EUR 410/month for labor costs, welding shield gas and energy)<br>Reduced over-processing | Energy consumption reduced by 38%<br>Scrap reduced by 66% (400 kg per month)<br>Reduced consumption of welding shield gas due to reduced rework<br>Average reduction of 30% (ca. 3.5 kg) in raw material used in each product<br>Reduction of 70% of the chemicals used for cleaning |
| Sobral *et al.* (2013) | Optimization through lean production practices | Cleaning rework was eliminated | After implementing JIT, storage time was reduced and protective oil layer on parts is not needed anymore; reduced water consumption since washing was eliminated<br>Reduced glue consumption during manufacturing process |

**Table A1.**

(*continued*)

| Authors (year) | Description of measures | Economic effects | Ecological effects |
|---|---|---|---|
| Stoll *et al.* (2008) | Cooling during metal cutting (machinery and workpiece) changed from wet machining to minimum quantity lubrication | Life cycle costs improved by 15%<br>Reduced efforts in handling of contaminated chips | Lower consumption of metalworking fluids (minus 113,500 l p.a.)<br>Reduced water consumption (minus 1.14 m l p.a.)<br>Reduced electrical power consumption (900,000 kWh p.a.)<br>Reduced filter media and disposal, lower compressed air usage<br>Reduced waste water treatment, lower air emissions<br>Higher recycle value for dry chips |
| Takada *et al.* (2008) | Integration of two or more fabrication processes into a single process by using multi-tone mask technology | Amount and number of material and processes are reduced<br>Cost and time reduction | Less waste produced, less energy consumed |
| Tamosiunas (2014) | Technological upgrades, automating the majority of operations, increasing the level of product heterogeneity, higher level of replication of operations per product category; Employees were trained and re-assigned new tasks or rotated focusing on the customer | Sales increased by 16% | Carbon emissions per $m^3$ of plywood produced decreased by 22%<br>Electrical energy consumed for manufacturing (per $m^3$ of product) reduced by 26%<br>Thermal energy consumed for manufacturing (per $m^3$ of product) reduced by 13%<br>Consumption of motor fuel decreased by 22% |
| Tang *et al.* (2016) | Algorithm (computerized batching) replaced rule-based (manual) planning approach for batch annealing process | Annual net profit increase of at least USD 1.76 m | Decreased $CO_2$ emissions<br>Reduced consumption of coal, protective gas, electricity and water |
| Tasdemir and Gazo (2019) | Among others benchmarking (KPIs) and root cause analysis lead to<br>- changed material procurement, picking and release<br>- improved facility layout<br>- implementation of 5S and Kanban posts | Financial performance improved from 33% loss to 46% profit<br>Non-value-added time reduced by 89%, value-added-time reduced by 48%, total lead time reduced by 86%, reduced cycle times<br>Labor costs per batch decreased by 42%, material costs decreased by 41%, transportation costs decreased by 40%<br>Reduced defect rate | Reductions in $CO_2$ emissions by 55%<br>Energy consumption reduced by 50%<br>Solid waste generation decreased by 72%<br>Net water footprint did not change |

(*continued*)

**Table A1.**

| Authors (year) | Description of measures | Economic effects | Ecological effects |
|---|---|---|---|
| Teng *et al.* (2020) | Structured analysis (incl. waste reduction algorithm) and debottlenecking capacity by changing configurations (T) | Energy consumption is reduced by 93%<br>ROI of 58,36%<br>Payback period of 65 months | Global warming potential reduced by 94% |
| Thanki and Thakkar (2020) | Case 1: Implementation of 5S, Kaizen, TPM<br>DfE | Profit decreased by 68% while costs for raw material decreased by 59% and energy costs decreased by 46% | Solid waste decreased by 69% |
| | Case 2: 5S | Profit increased by 30%<br>Costs for raw material increased by 30% and energy costs increased by 22%<br>Lead time decreased by 31% | Waste stayed on same level |
| | Case 3: 5S, TPM | Gross profit decreased by 13% while costs for raw materials decreased by 10%. Energy costs increased by 11% | Solid waste increased by 60% |
| | Cases 4: 5S, Kaizen, SMED, TPM<br>Focus on optimum use of natural resources | Profit increased by 370% while costs for raw material decreased by 37% and energy costs increased by 15% | Solid waste increased by 52% |
| | Case 5: 5S, Kaizen, SMED, TPM, DfE, 3R | Gross profit increased by 18% while costs for raw materials increased by 23%<br>Energy costs decreased by 2%<br>Lead time decreased by 60%<br>Significant improvement of product quality | Waste stayed on same level |
| | Case 6: 5S, Kaizen, SMED, TPM<br>Focus on optimum use of natural resources | Profit decreased by 38%<br>Costs for raw material increased by 11% and energy costs increased by 18% | Solid waste increased by 28% |
| | Case 7: 5S, Kaizen, TPM, 3R | Profit decreased by 10% while<br>costs for raw material decreased by 7% and energy costs increased by 15% | Solid waste increased by 5% |
| | Case 8: 5S, Kaizen, DfE, 3R | Profit increased by 49% while costs for raw material increased by 39% and energy costs decreased by 10% | Solid waste increased by 12% |

**Table A1.**

(*continued*)

| Authors (year) | Description of measures | Economic effects | Ecological effects |
|---|---|---|---|
| Tiwari *et al.* (2020) | Improvement measures (esp. additional equipment and employee training) were identified and implemented through following a framework | 89% cost savings<br>Defect rate decreased by 92%<br>Machine setup time reduced by 80% | $CO_2$ emissions reduced by 95%<br>Scrap reduction of 96% |
| Tokawa *et al.* (2001) | Application of dry hobbing machines with coolant-free swarf discharge capability | Machining costs reduced by 34%<br>Tool cost reduced by 23% since tool life was extended by five times<br>Labor cost per workpiece reduced by 38% due to doubled cutting speed | Coolant is completely avoided |
| Triebswetter and Hitchens (2005) | Replacement of coal by alternative fuels (e.g. used tires, paper waste) | EUR 125 saved per ton of replaced coal (save energy costs amounting to 7.5% of annual turnover) | One ton of coal is replaced by two tons of alternative fuels |
| | | save energy costs amounting to 1.7% of annual sales | Use of 17% alternative fuels |
| | | save energy costs amounting to 2.5% of turnover | 20,000 t of tires are used as fuel instead of coal |
| Vargas and Scott (2017) | Case 1: Semiautomated process with new technology<br>Case 2: Floor layout was redesigned to resolve water issues | 50% less operators needed<br>Process time reduced by 62%<br>Improved productivity | Consumption of natural gas significantly reduced by 11,000m$^3$ p.a<br>Water consumption reduced by 3.3 m l<br>27,000 l of pit-cleaning waste water p.a. avoided |
| | Case 3: Reuse process and more efficient waste-segregation | Significant reduction of work hours | Avoidance of 90 kg of hazardous waste p.a |
| | Case 4: Development of a distillation process that allowed reuse of hazardous chemicals | Procurement of some chemicals are reduced by 61% | Up to 90% of some chemicals can be reused |
| | Case 5: Extended use of coolant via inverse-osmosis and quality monitoring | Less downtime<br>Reduced product handling | Reduction of 87,500 l of waste coolant p.a |
| | Case 6: Ultrasonic cleaner instead of manual use of solvent-based cleaner | Shorter cycle time | Replacement of 1,000 aerosol cans p.a |
| Veltri *et al.* (1999) | Recycling strategy (T) | Cost saving potential of 46%<br>Net present value of recycling is estimated with USD 4.3 m | 70% of ultrapure water can be recycled |

(*continued*)

**Table A1.**

| Authors (year) | Description of measures | Economic effects | Ecological effects |
|---|---|---|---|
| Vinodh *et al.* (2016) | Optimized power consumption through machine settings, waste-water treatment, standard operating procedure, 5S activities for two processes, operator workload balancing | Manufacturing costs reduced by 19%<br>Cycle time reduced by 6%<br>Lead time reduced by 52%<br>Value-adding costs reduced by 5%<br>Non-value-adding costs reduced by 38% | $CO_2$ emissions reduced by 20%<br>Consumption of electricity reduced by 30% |
| Wills (2009) | Replacing hazardous solvent by water-based solvent | Savings of USD 6,000 p.a. (payback period of retooling 6 months) | Emission of VOC reduced by 62% |
| | Replacing spray paint by powder coating, using different kind of glue | Savings of USD 1m p.a. (payback period of one year) | Significant reduction of emissions (esp. VOC) and waste |
| Yamazaki (2017) | Integrated and synchronized manufacturing line with downsized equipment | Production costs reduced by 33%<br>Reduced setup time | Energy consumption reduced by 50%<br>Area occupied by equipment reduced by 20% |
| Yang and Feng (2008) | Transformation to circular corporation | Sales increased by 153%<br>Profit increased by 5,521%<br>High investments | Water consumption reduced by 35%<br>COD decreased by 62%<br>$SO_2$ emissions reduced by 59% |
| Yue and You (2013) | Optimization of batch scheduling | Productivity increased by 23% | Environmental impact per unit reduced by 1% |
| Yun *et al.* (2014) | Cold extrusion is applied to manufacture helical gears | Increased productivity<br>Hardness of gear increased by 37% | Energy consumption reduced by 25% (single-type gear) and 49% (double-type gear) compared to conventional machining<br>$CO_2$ emissions reduced by 40%<br>Material recovery rates increased by 58% (single-type gear) and 91% (double-type gear) |
| Zhang *et al.* (2018) | Real-time scheduling for remanufacturing of automobile engines via IoT | Manufacturing costs reduced by 34% | Energy consumption reduced by 34% |
| Zhang *et al.* (2016) | Recovery of industrial waste heat via steam turbine | Payback period of 2.3 years | Burning of 9,853t of standard coal equivalent were avoided |

**Table A1.**

(*continued*)

| Authors (year) | Description of measures | Economic effects | Ecological effects |
|---|---|---|---|
| Zhi-dong *et al.* (2011) | Identification and analysis of different options regarding "'cleaner production" (e.g. technological modification, waste treatment and utilization) | Low cost options resulted in benefits of CNY 44.8 m<br>Middle/high cost options added CNY 345m of benefits<br>Expenditure of coal and water per CNY 10k output are reduced by 2.2 and 1.5% respectively | COD reduced by 35% (annual emission reduced by 465 t)<br>Ammonia nitrogen concentrations reduced by 72% (annual emission reduced by 84 t)<br>Phosphorus concentrations reduced by 76% (annual emission reduced by 2.4 t)<br>Solid waste reduced by 3% |
| Zhu *et al.* (2007) | By-products became additional production lines including a heat and power facility<br>Article is about a corporate group representing six cases | "Quality premium" of 10% for main product<br>Reduced input costs (recovered alkali is half the price of purchased alkali)<br>Reduced production costs | Utilization of by-products from local competitors which would be discarding or incinerating otherwise<br>Reduced pollution (e.g. recovery rate of alkali is 80%) |

**Note(s):** T: theoretical work; 3R: reduce, reuse, recycle (UNEP, 2004), 5S: workplace organization method; BOD: biochemical oxygen demand; CNC: computer numerical control; $CO_2e$: carbon dioxide equivalent; COD: chemical oxygen demand; GHG: greenhouse gas; JIT: just-in-time production; MTTR: mean time to repair; MTBF: mean time between failure; OEE: overall equipment effectiveness; SMED: single minute exchange of die; TPM: total productive maintenance; VSM: value-stream mapping; VOC: volatile organic compound
**Source(s):** Authors' own elaboration

**Table A1.**

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