Industrial symbiosis profiles in energy-intensive industries: sectoral insights from open databases

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Abstract

Process industries are the foundation of the European economy, transforming raw materials into building blocks for strategic products and applications in today's society. Such industries range from steel, cement, or minerals to chemicals such as lubricants for wind turbines and polymers that prevent waste in logistic supply chains. The downside of this foundation industry is its high environmental impact regarding emissions, and intensive use of energy and resources. One of the key strategies to address such challenges is industrial symbiosis: various industries establish collective efforts to find value while transitioning to a more circular economy. This paper presents an exploratory analysis of databases on IS case studies. We used the European standard classification for economic activities (NACE) to draw industrial sector profiles for the most relevant energy-intensive industries: chemicals, steel, and cement, coupled with urban synergies. The majority of the synergies includes the chemicals sector with most commonly shared streams being energy, water, and carbon dioxide. IS cases are ranked in terms of frequency, then classified in topical groups and finally, the sustainability impact of the different categories is discussed. The outcome is a methodology to frame and assess industrial symbiosis case collections useful for future exploring and exploiting circularity projects in public and private organisations.

Keywords

Energy-intensive industry, industrial symbiosis, circular economy, sustainability, databases

Highlights

- Sectoral profiles for industrial symbiosis with standardised sectors and resource sharing
- Focus on cross-sectoral exchanges in process industry sectors: chemicals, steel, and cement including urban synergies
- Insights on the technology and sustainability gains per shared resource category
- New method to develop continuous improvement in industrial symbiosis databases

1. Introduction

1.1 Energy-intensive industries and emerging policy

In the last decade, a number of reports and policy recommendations at global and European levels have paved the way to take firm actions regarding greenhouse gas (GHG) emissions and resource depletion to prevent major and irreversible consequences to the environment, to ecosystems, and to human society (Rockström et al., 2009; IPCC, 2018). A crucial initiative was the Paris Agreement at the Climate Change Conference in 2015, where 195 countries jointly committed to limit global temperature rise below 1.5°C (European Commission, 2016). It triggered a series of policy and strategy actions taken by the European Commission to enhance the transition towards a more sustainable economy. The most recent strategy in this area is the EU Green Deal (European Commission, 2019a), resulting in the Climate Law (European Commission, 2020a), which enshrines 2050 climate-neutrality into law. Concerning resource preservation, the most important initiative is the deployment of the circular economy concept, growing its policy relevance in Europe (European Commission, 2020b) and involving industry, society and academia as a whole.

In this context, energy-intensive industries (EIIs) have a significant role to play (HLGEEIs, 2019). In 2018, the total direct GHG emissions from EIIs in the EU represented 15% of EU-28 total GHG emissions (European Commission, 2020c). In the meantime, between 1990 and 2015, EIIs reduced their GHG emissions by 36%, accounting for 28% of the total economy-wide emission reductions by the EU (Wyns et al., 2018). These decreases are related to technical factors such as improvements on energy efficiency and resource innovation like the use of biomass as fuel, but also to non-technical influences such as lower production levels following the economic crisis of 2008 (Wyns et al., 2018). Similar factors were found in a Canadian study, finding five change drivers for CO_2 emissions in the industry: activity level, industry structure, energy intensity, fuel mix, and emission factors (Talaei et al., 2020). Among EIIs, chemicals, steel, and cement industries represent almost 70% of the CO_2 industrial emissions in the EU ETS in 2018 (de Bruyn et al., 2020). Thus, improving the energy and resource efficiency of these three sectors is significant for achieving the EU's climate goals.

1.2 The key IIEs sectors: chemicals, steel, and cement

The role of the chemicals, steel, and cement sectors in the EU is crucial not only in terms of transitioning towards climate-neutrality; it also implies issues such as global competitiveness and regional circularity due to their high energy and resource demand and impact on productivity and employment levels.

In 2018, the chemicals industry in Europe represented 20.7% of the world output sales in euros (CEFIC, 2020a). The sector is a supplier to virtually every other industry in Europe, producing about 330 Mt of product per year (Elser and Ulbrich, 2017) but also generating CO_2 emissions at 27% of the total industrial CO_2 emissions in the EU ETS in 2018 (de Bruyn et al., 2020). In the last decades, many efforts have been made to reduce process emissions via energy efficiency. The energy consumption per unit of production in the chemical industry, including pharmaceuticals, was nearly 55% lower in 2017 than in 1991 (CEFIC, 2020a). One of the key features enabling the sector's lower carbon transition is its clustering capacity. This does not only enhance competitiveness (Elser and Ulbrich, 2017; Ketels, 2007) but also answers socio-environmental questions by making effective synergies between different process units and sectors or communities in a specific region (Cervo, 2020; Lowe and Evans, 1995).

In the EU, the steel sector accounted for 10% of the world output (metric tonnes) in 2019 (EUROFER, 2020). Steel is fundamental for both the manufacturing and the construction industry and thus for the logistic development of any region. Such importance implies a high demand for raw materials and an equally high amount of emissions. The industry requires about two tonnes of material (iron ore and coke) to produce one tonne of steel (World Steel, 2019). In 2018, the steel sector made up for 22% of the total industrial CO_2 emissions in the EU ETS (de Bruyn et al., 2020). In contrast, the EU steel industry has reduced its energy consumption by 50% over the last 40 years, thanks to higher scrap recycling levels and a decrease in production (European Commission, 2014).

In 2018, the production of cement in EU-28 represented 4.4% of the total world production (metric tonnes) (CEMBUREAU, 2019). Cement is fundamental for building durable structures since it is a hydraulic binder in concrete (Elser and Ulbrich, 2017). The CO_2 emissions from the sector in Europe take up a 21% share of the total industrial CO_2 emissions in the EU ETS in 2018 (de Bruyn et al., 2020). An important aspect of this industry is its ability to use fuels derived from waste and biomass to produce heat in its kilns. In Europe, this amounts to ca. 40% of the fuel supply for thermal energy in the grey clinker production (De Beer et al., 2017). Between 1990 and 2017, the EU-28 cement industry has reduced its gross CO_2 emissions per tonne of product by 13% (CEMBUREAU, 2019).

In the context of the circular economy, the relations between industries and cities are crucial. Urban districts refer to "the close spatial proximity of areas with a high population density" (Joint Research Centre (European Commission), 2019). The EU had an urbanisation rate of 72% in 2015 and a population density of 3 000 residents per km^2. Most citizens live in mid-sized cities (Joint Research Centre (European Commission), 2019). High-density urbanised areas have implications for industries in terms of product/service demands and the availability of qualified professionals. Also, European cities enable a concentrated demand of industrial products and can also recirculate resources back to the industry at scale. In terms of energy use, at a global level, cities are attributed about 70% GHG emissions while being especially vulnerable to the impacts of climate change (Joint Research Centre (European Commission), 2019). Hence, the collaboration between cities and industries towards common goals is a key component of the European policy agenda.

1.3 Circular economy, industrial symbiosis (IS), and case collections

In its Circular Economy Action Plan, the European Commission refers to the circular economy as a regenerative economic model that keeps the use of resources within the planetary boundaries while reducing the footprint of consumption in Europe (European Commission, 2020b). The ELLEN MACARTHUR FOUNDATION (EMF, 2013), one of the foremost promoters of the concept, established three actionable principles related to the circular economy concept: (1) the preservation of natural capital, referring to the control of non-renewable resource stokes and the balance of resource flows; (2) the optimisation of resource yields, referring to the (re-)circulation of products, components, and material in use at the highest utility; and (3) the fostering of system effectiveness, referring to the assessment and management of externalities. Also, the sustainable product policy framework (European Commission, 2020b) addresses circularity in three aspects: designing sustainable products, empowering consumers, and interrelating production processes. The latter promotes and facilitates industrial symbiosis by developing an industry-led certification system.

In this context, IS plays its role as a business archetype based on a cooperative network to provide a competitive advantage based on shared resources (infrastructure, by-products, and joint services) (Baldassarre et al., 2019; Chertow et al., 2008). Such an approach leads to create value from waste while improving resource efficiency (Van Eetvelde, 2018). Jacobsen (2006) provided an in-depth analysis of the Kalundborg cluster, presenting quantitative insights on the economic and environmental performance enabled by IS. He clarifies that economic motivations are often generated upstream as well as downstream, beyond the value of exchanged by-product, thus encouraging the dual perspective of individual sites and collective value chains. Going beyond Kalundborg, Chertow (2007) provided a historical view on IS in cross-sectoral clusters, highlighting the need to identify precursors for symbiosis with resource sharing projects such as co-generation and waste-water reuse.

Baldassarre et al. (2019) proposed the synthetic conceptualisation of IS from a circular economy and industrial ecology perspective. On the one hand, IS focuses on business viability and operations (circular economy), while on the other hand, it focuses on process understanding and environmental impacts (industrial ecology). However, reaching a common understanding of IS presents different challenges due to the diversity of actors and situational factors involved (Boons et al., 2017). The concept builds from the mutual interaction of a variety of entities initiated by a variety of drivers (Van Eetvelde, 2018; Abreu and Ceglia). Boons et al. (2017) proposed terminology for IS as a process of connecting flows among industrial actors, trying to address the complexity of the concept by defining different dynamic models. A further attempt to establish standard IS principles was made in a documented CEN-CENELEC workshop with the contribution of academic and non-academic participants (CEN-CENELEC, 2018). A recent bibliographical study with a selection of more than 600 articles over a period of 30 years (Mallawaarachchi et al., 2020) proves that the sustainability of material and energy interactions has been central to the concept. IS has been expanded extensively in the last five years to include non-material resources, contextual factors (cultural, political, spatial, etc.), and the impact of externalities.

The key aspect of sustainability in IS refers to establishing multidimensional synergies across different industries. Such synergies can be economical, social, or environmental, as emphasised in recent European projects and studies (SCALER project, 2020; EPOS project, 2019). The economic synergies result from the generation of marketplaces for underused resources creating revenue streams and cost savings (Albino and Fraccascia, 2015). The social impact often refers to generating jobs and enhancing relationships with communities surrounding the industries. This is of special relevance for urban industrial symbiosis, fulfilling mainly infrastructure needs of urban areas related to energy and material flows (European Commission, 2019b; Ažman Momirski et al., 2021). In terms of environmental performance, the synergy point lies in material and emissions efficiencies promoting resource conservation and avoiding associated environmental impacts (Axelson et al., 2021). Such efficiencies, however, are not always granted due to circular economy rebound effects (Zink & Geyer, 2017), symbiotic rebounds (Figge & Thorpe, 2019), and/or additional by-product processing needs (Mohammed et al., 2018). Thus, the assessment of IS opportunities at different stages of IS projects is required, from the initial identification to the ongoing documentation (Maqbool et al., 2019; Yeo et al., 2019). The database collection developed in this article focuses on the first stage of identifying sustainable cases for IS, where a first screening of the sustainable impact due to links among sectors is presented.

In the last fifteen years, over 130 million euros have been invested in Europe to develop tools that enable a broad implementation of industrial symbiosis (Maqbool et al., 2019); and still, there is potential for further exploitation (Azevedo et al., 2020; Neves et al., 2020). Barriers related to non-technological factors such as low trust among partners, lack of information, and non-supportive environmental legislation have been highlighted (Neves et al., 2019; Van Eetvelde, 2018; Golev et al., 2015). In order to fill the information gap, several studies and projects have been done, building databases and reports to reference IS cases using various approaches. In 2002, Pellenbarg (2002) published a study focusing on the Netherlands under the concept of sustainable business sites. With a similar site-based approach on eco-industrial parks, Susur et al. (2019) presented an overview of 104 sites located worldwide. Neves et al. (2020) made a literature review of more than 500 papers from cases around the world, showing that China and the USA are the countries with the highest number of studies. Still, most of the analysed cases are in Europe. In one of the latest studies on IS databases, Jato-Espino and Ruiz-Puente (2020) performed an analysis of open access IS databases clarifying links between different sectors with a focus on correspondence, network, and correlation analysis. It provides a solid base to explore further IS cases for sectors of main relevance towards resource and climate neutrality, such as chemicals, steel, and cement.

The state-of-the-art of IS research projects in EIIs have a wide range of applications but also show converging approaches. Recent European projects have focused on the identification of IS cases at different levels (Maqbool et al., 2019). The MAESTRI project developed a knowledge depository targeting practitioners that aim at IS replication (Benedetti et al., 2017; Evans et al., 2017). The EPOS project generated a collection of generic cases for replication in cross-sectoral clusters (EPOS project, 2019). The SCALER project published several reports on 100 synergy schemes with an estimated added value of 8 billion euros for the EU and a significant reduction of the environmental impact (Azevedo et al., 2020). Such European projects have taken a sectoral approach towards a regional replication. In the EPOS project, blueprints of various industrial sectors have been developed to enable communication and optimisation between sites and sectors with differing activities (Cervo et al., 2020; EPOS project, 2019a). Also, the use of established classification schemes such as NACE codes for economic activities in the European Union (Eurostat, 2008) has been introduced to access databases and disseminate IS cases to a broader audience (Evans et al., 2017).

This paper aims at integrating successful approaches from state-of-the-art projects and IS database research to perform an exploratory analysis of industrial symbiosis in key industrial sectors by making use of public IS databases and using standard classifications for industrial activities (e.g., NACE), resources categories, and selected statistics. The objective is to conceptualise and apply industrial sector profiles for IS in terms of cross-sectoral collaborations. Such profiles specify the role a sector plays in the synergy, the partnership and the resources involved. They also define what technologies could enable IS and help to provide insights on the sustainability of the cases.

In the following section, methodological aspects are detailed, such as the definition of sector profiles, the approach to IS in the context of data processing, the selection and validation process for IS cases, and the method for categorising exchanges. In section 3, the results are presented per sector in terms of categories of exchanged resources and partnering sectors, including a focus on the interlinks between sectors, the related technologies, and sustainability insights per sector. In section 4, a discussion is raised about missing links among process industries, next to a broader perspective of sustainability in IS cases. The section includes the learnings gained by developing the IS profiles and working with public databases; such learnings are integrated into a new method for continuous improvement. Finally, section 5 presents overall conclusions summarising the main research findings and indicating further research lines.

2. Methodology

The process to develop sector profiles from IS database collections is illustrated in Figure 1. It starts with sector standardisation, which consists of three sub-steps: selection of industrial sectors (chemicals, steel, or cement), selection of a suitable standard code for economic activities (NACE for Europe), and definition of the sectors in the selected code. The next stage concerns the selection of IS database collections. The MAESTRI knowledge depository (Benedetti et al., 2017; Evans et al., 2017) is used as the central collection as there currently is no other suitable semi-standardised IS database. The EPOS generic cases (EPOS project, 2019) and the SCALER synergies (SCALER project, 2020) are supplementary references. In the next stage, the findings are validated, with consistency checks and clustering of terms taking place. This results in sector profiles that specify the role a sector plays in the synergy, the partnership, and the resources involved in the IS case. In the final stage, cross-sectorial links are made in terms of technologies and sustainability, as explained in the following sections.

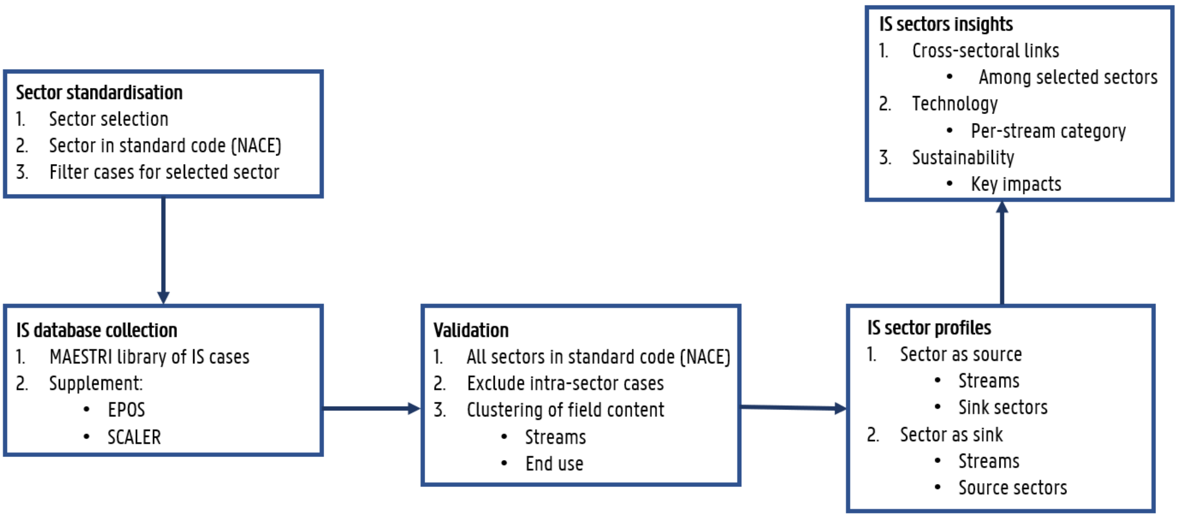

Figure 1 Sector profile generation scheme: A step-by-step method to define and present IS for EIIs.

2.1 Sector standardisation

The first step of the methodology is sector standardisation. Industrial IS actors are grouped per the corresponding sector according to NACE codes to enable the use of relevant databases (MAESTRI). For the cement and steel sectors, single NACE codes are available and are C2351 and C2410, respectively, while for the chemicals sector, several NACE codes are used (C19, C20, C21, C22) based on the work of Cervo (2020). Urban districts or cities were included as a sector without a standard code (Not Applicable or NA).

2.2 IS database collection

The second step of the methodology is the IS database collection. A systematic comparison of public access IS databases (Jato-Espino & Ruiz-Puente, 2020) highlighted that the MAESTRI project collection (Evans et al., 2017) could be used as the main source of information due to its completeness and traceability. The MAESTRI database contains 424 binary synergy cases (two sectors per case) and provides a structure using standardised schemes (NACE, European waste codes, among others) with clearly linked references. This database was designed as a tool for systematic filtering of cases to promote IS among companies (Benedetti et al., 2017). The selection criterion was to include publicly reported cases already labelled as industrial symbiosis to promote IS solutions by mimicking existing cases and extending their replication potential (Benedetti et al., 2017).

The MAESTRI database provided a starting point. It was filtered for the NACE codes of the selected sectors, which led to 210 cases. Additional cases were included following the MAESTRI's selection criterion to fill the gaps among sectors across the different resource categories, amounting to 252 cases in total (Appendix A). In particular, 16 binary cases were added from the EPOS generic cases and 26 more cases were taken from the SCALER dataset. In this paper, the tool is used to build a database of cases, a so-called case-base suited for developing insight on IS at a sector level, not only by bringing statistical analyses but also by understanding drivers and barriers related to exchanges among sectors in terms of technology and sustainability.

Table 1 provides a general overview of the databases:

Table 1 Collected IS databases characteristics. They share the common goal of replication of IS cases across Europe.

Project	Goal	Regional scope	Date	Sectors per case	# cases	# selected cases	Reference
MAESTRI Library	EU replication	World	2017	2	424	210	Evans et al., 2017
EPOS IS case watch	EU replication	Europe	2019	3-5	21	16	EPOS project, 2019
SCALER 100 synergies dataset	EU replication	Europe	2019	2	100	26	SCALER Project, 2020

As compared to the MAESTRI database, which has no geographical restriction, the EPOS case collection was developed for specific industrial clusters and technologies in Europe (EPOS project, 2019). Similarly, SCALER 'synergy types' aim at replication and add a deeper level of techno-economic assessment plus an environmental appraisal (SCALER project, 2019). The three databases together bring variety to the aggregated database and enhance the IS identification capacity.

2.3 Validation

The third step of the methodology is the validation of the collected cases. The MAESTRI database (Evans et al., 2017) included NACE codes for each IS case. A revision of the codes was done for the cases involving chemicals, steel, and cement industries. A resource category was developed grouping streams from different sectors. A first category was called 'energy', grouping sub-functions such as heating & cooling, fuel substitution (for heat generation), and electricity where its generation takes place as part of the synergy. Other streams were categorised as 'by-product' or 'waste', both functioning as (raw) material inputs. The waste category refers to any other material input with a specific European Waste Code as defined in the MAESTRI database. As the final category, 'water' was chosen despite the fact that water streams often have simultaneous functions as energy or by-product. However, when a specific use of water was reported in the synergy with energy use (heating or cooling), the stream was classified in the energy category.

To classify each stream into the above categories, the following method was used:

1. Is the stream substituting an energy input (heating/cooling/fuel/electricity)?
    - Yes: Classify as Energy
    - No: Go to 2
2. Does the stream involve mainly water?
    - Yes: Classify as water
    - No: Go to 3
3. Does the stream have a waste code?
    - Yes: Classify it as waste
    - No: Classify as by-product (ranked by sender/status before the symbiosis happens)

Finally, a consistency check of terminology was performed for resource types, stream names, sector allocations, and references.

For the present research, IS cases are exclusive collaborations between different sectors; therefore, intra-sectoral cases are not included as part of the validation. Chertow et al. (2008) made a distinction between industrial symbiosis activities occurring in two types of systems: single industry-dominated clusters and multi-industry ones. They pointed out that in the latter, most activities are done in isolation. However, due to the variety of resource inputs and outputs, there may be a high potential for symbiosis, as evidenced in the Kalundborg model. Therefore, it is crucial to focus on cross-sectorial collaborations to enhance industrial exchanges.

2.4 Sector IS profiles & insights

The fourth step of the methodology is the creation of sector profiles. Binary synergy models are used to represent industrial symbiosis and organise case studies (Figure 2). In such models, each sector can have two roles for the other sector: either as a source or a sink for a specific stream. A source role implies the supply of a stream to the other sector; a sink role receives a stream from the other sector. To emphasise a network approach, the terms 'sink' and 'source' for sectors were selected, reflecting different methods for optimising networks of resources (Kastner et al., 2015).

Figure 2 Synergy model: Industrial sector as a resource source and as a sink.

Therefore, the IS profile of a sector represents the collection of streams and partnering sectors based on case frequency. The profile is dual due to the binary model for IS roles: a sector can operate from both sides of an IS case, as a source or as a sink.

2.5 Sector IS insights

The fifth and final step of the methodology consists of analysing the relations across sectors in terms of enabling technologies and sustainability insights.

The first objective is to specify the synergies among the main sectors of analysis: chemicals, steel, and cement. A matrix (Table 3), including the three sectors complemented with urban districts profiles, is built to clarify any connection and identify the type of relation in terms of role (source, sink, or both).

Secondly, enabling technologies refer to the technical processes that act upon the streams to enable symbiosis. Such technologies can be as simple as transport needs or as complex as implementing emerging processes at scale, such as installing carbon capture units.

Lastly, technology aspects are closely related to the sustainability insights of the different cases. Relevant insights in the results section are developed in the context of IS identification in relation to the central resource to the synergy and the technology. The insights aim to screen a sustainable case.

3. Results

Results are presented with a top-down approach, starting in section 3.1 with the overview of the IS profiles of main sectors. In section 3.2, a more in-depth sector by sector analysis is done for chemicals, steel, cement, and urban districts respectively.

3.1 IS sector profile overview

Table 2 gives an overview of the sector profiles in terms of role (sources or sinks) and stream category (energy, waste, by-product, water).

Table 2 EIIs sector profiles overview. Each sector has a dual role (source and sink) across four resource categories.

Sector	Role	%*	# IS cases per category				Number partnering sectors
			Energy	Waste	By-product	Water	
Chemicals	Source	44%	18	8	26	15	23
	Sink	56%	32	29	19	7	23
Steel	Source	72%	15	36	6	3	14
	Sink	28%	5	13	2	3	6
Cement	Source	19%	5	3	3	0	7
	Sink	81%	7	33	4	3	16
Urban	Source	69%	2	16	0	4	6
	Sink	31%	8	1	0	1	3

*% of IS cases for which the sector has the corresponding role

A total of 252 synergy cases were categorised as waste, energy, by-product, and water. 41% of these cases concern waste, 27% energy, 21% by-product, and 11% water.

In the **waste** category, the most frequent streams are slag from steel furnaces (Appendix A), followed by waste plastics and fly ash streams. The most frequent **by-product** exchanges are carbon dioxide, hydrogen, and sludge with a strong participation of the chemicals sector.

In the **energy** category, heating networks and co-generation (electricity) cases are the most frequent. Heating and cooling processes account for 60% of the energy cases while electricity synergies represent 21%, involving chemical, steel, cement, aluminium, energy, and paper sectors in co-generation schemes. The remaining cases (19%) relate to the use of alternative fuels, making use of fuel gas, industrial waste, and packaging waste. Finally, **water** streams that are not related to energy processes are not frequent but still reported as process water.

Table 3 presents the links and gaps in terms of IS roles (sink or source) of the main sectors among themselves. In the table, the reference sector is either a sink or a source for the specific resource category in the header (waste, energy, by-product, and water). For example, chemicals is a waste sink for steel, cement, and urban districts, and also a source for synergies with cement. Table 3 shows gaps when there are no reported links between sectors for a specific category. The only gap common to all sectors is for valorising by-products in urban districts. This may be related to the legal status of by-products, an aspect that is further discussed in section 4.1.

Table 3 Main EIIs sectors have a role for each resource category. The sectors make synergies as a sink or source among themselves except for urban districts in terms of by-product cases.

Reference sector	Waste	Energy	By-product	Water	Partnering sector
Chemicals	sink	both	both	both	Steel
	both	both	source	source	Cement
	sink	both	-	both	Urban
Steel	source	both	both	both	Chemicals
	source	both	sink	source	Cement
	both	source	-	sink	Urban
Cement	both	both	sink	sink	Chemicals
	sink	both	source	both	Steel
	sink	both	-	sink	Urban
Urban	source	both	-	both	Chemicals
	both	sink	-	source	Steel
	source	both	-	source	Cement

3.2 IS sector profile

In this section, the IS sector profiles are presented with a higher level of details in terms of partnering sectors and resources used in the synergies.

3.2.1 Chemicals sector profile

Out of the 252 cases analysed (Appendix A), the chemicals sector is involved in 154 of them (61%). This already highlights the key role of the chemical industry in implementing IS as this sector is able to transform and valorise a large variety of materials. Table 4 and Table 5 respectively display the results of the IS database analysis for the chemicals sector as a sink and as a source.

Table 4 Chemicals sector profile, as a sink, has most frequent IS cases with energy supply, steel, and non-ferrous metal sectors.

Sector	NACE	Energy	Waste	By-product	Water	Total cases
Electricity, gas, steam, and air conditioning supply	D35	19	0	0	4	23
Manufacture of basic iron and steel and of ferro-alloys	C2410	6	4	3	1	14
Other non-ferrous metal production	C2445	0	3	9	0	12
Manufacture of pulp, paper, and paperboard	C1710	2	4	1	0	7
Urban district	NA	1	2	0	1	4
Manufacture of cement	C2351	2	1	0	0	3
Manufacture of sugar	C1081	0	2	1	0	3
Growing of non-perennial crops	A0110	0	2	0	0	2
Cutting, shaping and finishing of stone	C2370	0	0	2	0	2
Distilling, rectifying, and blending of spirits	C1101	0	2	0	0	2
Processing and preserving of fish, crustaceans, and molluscs	C1020	0	1	1	0	2
Raising of other animals	A0149	0	1	0	0	1
Water collection, treatment, and supply	E3600	0	1	0	0	1

Mixed farming	A0150	0	1	0	0	1
Manufacture of paper and paperboard	C1712	0	1	0	0	1
Aluminium production	C2442	1	0	0	0	1
Manufacture of beer	C1105	0	1	0	0	1
Manufacture of jewellery and related articles	C3212	0	0	1	0	1
Manufacture of soft drinks; production of mineral waters and other bottled waters	C1107	0	1	0	0	1
Production of electricity	D3511	0	0	0	1	1
Manufacture of veneer sheets and wood-based panels	C1621	1	0	0	0	1
Manufacture of food products	C108	0	0	1	0	1
Growing of perennial crops	A0120	0	1	0	0	1
Manufacture of other non-metallic mineral products	C2300	0	1	0	0	1
Total cases		**32**	**29**	**19**	**7**	**87**

Table 5 Chemicals sector profile, as a source, has most frequent IS cases with energy supply, cement, and non-ferrous metal sectors.

Sector	NACE	By-product	Energy	Water	Waste	Total cases
Electricity, gas, steam, and air conditioning supply	D35	3	10	7	0	20
Manufacture of cement	C2351	2	3	1	1	7
Other non-ferrous metal production	C2445	4	0	1	0	5
Manufacture of pulp, paper, and paperboard	C1710	3	0	1	0	4
Aluminium production	C2442	3	0	0	0	3
Manufacture of basic iron and steel and of ferro-alloys	C2410	1	1	1	0	3
Treatment and coating of metals	C2561	3	0	0	0	3
Manufacture of prepared feeds for farm animals	C1091	0	0	0	2	2
Manufacture of soft drinks	C1107	1	1	0	0	2
Growing of vegetables and melons, roots, and tubers	A0113	1	1	0	0	2
Production of electricity	D3511	2	0	0	0	2
Urban district	NA	0	1	1	0	2
Growing of cereals (except rice), leguminous crops, and oil seeds	A0111	0	0	1	1	2
Waste treatment and disposal	E3820	0	0	1	0	1
Manufacture of plaster products for construction purposes	C2362	1	0	0	0	1
Mining of chemical and fertiliser minerals	B0891	0	0	1	0	1
Mining support service activities	B99	1	0	0	0	1
Water collection, treatment, and supply	E3600	1	0	0	0	1
Other processing and preserving of fruit and vegetables	C1039	0	0	0	1	1
Other business support service activities	N8299	0	1	0	0	1
Manufacture of macaroni, noodles, couscous, and similar farinaceous products	C1073	0	0	0	1	1
Mixed farming	A0150	0	0	0	1	1
Manufacture of articles of concrete, cement, and plaster	C236	0	0	0	1	1
Total cases		**26**	**18**	**15**	**8**	**67**

Among the 154 cases, circa one third (34%) involves the exchange of energy, over one quarter (29%) by-products, another quarter (24%) waste, and the remainder (13%) the exchange of water.

The energy sector (D35) exchanges most with the chemical industry, both from a source and sink side. This does not come as a surprise since chemical plants are highly energy-intensive and operate with power stations providing the utilities required to run the processes (Cervo, 2020).

Due to the wide variety of applications in the chemicals sector, a further fragmentation of the sector is shown in Figure 3 according to the previously selected NACE codes. Inorganic chemicals (C2013), petroleum products (C19), and fertilisers (C2015) are the most frequent segments within chemicals.

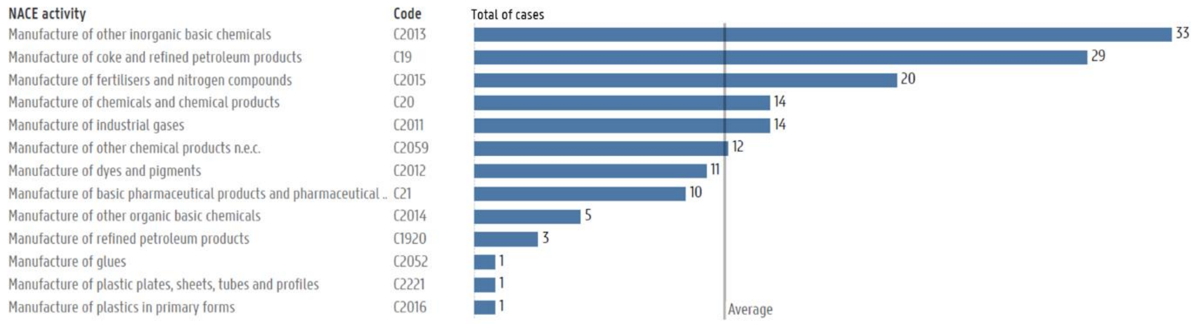

Figure 3 Chemicals segmentation for IS: Main chemical processes according to NACE activities include inorganic chemicals (C2013), petroleum products (C19), and fertilisers (C2015).

Considering the **chemicals sector as a sink**, one notices that the majority of exchanges (37%) involves energy. This is mostly explained by the tight relationships between the chemical industry and energy sectors (D35), as previously mentioned, but also by some interesting synergies with the steel sector (C2410) sending steam for heating purposes. Additionally, the chemical industry also receives many waste streams (33% of the sink exchanges), illustrating the capability of the chemical industry to transform waste into useful resources. Chemicals has also a growing number of by-product synergies with non-ferrous metal industries (C2445), since the streams have significant amounts of valuable metals for the chemical processes.

The manufacturing of other inorganic basic chemicals (C2013) is also frequently receiving streams (Appendix A). This can be explained by the fact that this category represents a multitude of chemical processes able to handle different types of streams (energy, by-product, and waste) and especially the multiple synergies with metal industries to recover the value from sludges and emissions. Also, the manufacturing of fertilisers (C2015) is one of the chemical processes that can take in a variety of wastes, such as organic residues, sludge, and sulphur (Appendix A). Last but not least, one can also notice specific exchanges, such as the valorisation of the gases produced during the steelmaking process by the chemical industry (Appendix A). These gases contain chemicals such as carbon monoxide or hydrogen that are readily used to synthesise new molecules (Bazzanella and Ausfelder, 2017).

Looking at the **chemicals sector as a source**, it is observed that the majority of exchanges (39%) relates to by-products. However, no particular industrial sector (except D35) is preferably receiving streams from the chemical industry. This phenomenon can be explained by the fact that the chemical industry is involved in the value chain of many different industries as it produces the building blocks that are used to manufacture new products. Some symbioses are also worth noticing (Appendix A), such as the use of carbon dioxide (produced by the chemical industry) by alumina refineries (C2442) to produce lime, which is used as an additive in the chemical process to improve product quality and reduce energy consumptions (Arıkan et al., 2019). Other promising cases include the use of CO_2 streams for mineralisation with applications that promise to keep the CO_2 in use for a longer term in the mineral (EPOS project, 2019), the steel (Huijgen et al., 2005), and the cement sectors (Huntzinger et al., 2009).

Another interesting symbiosis is the recovery of hazardous by-products, such as caustic soda and hydrochloric acid, by galvanic treatment plants (C2561).

The **chemical industry** is typically involved in symbiotic relationships with urban areas. Chemical processes either produce or use heat (exo- or endothermic reactions) and thus can function as a heat sink or source for nearby cities or industrial clusters. This presents opportunities for either industrial steam networks or direct district heating networks. A textbook example of such a synergy is the Kalundborg eco-industrial park in Denmark, where a refinery is providing heat to the city (Jacobsen, 2006; Symbiosis Institute, 2019). In such networks, pressurised water is often used as a medium to carry the heat from the chemical plant to the city, which also explains why the chemical industry can be seen as a source of water for urban districts.

Overall, the results indicate that IS and recycling waste have been part of the chemical industry's core business. The profile of the chemicals sector for symbiosis is very versatile. The chemical industry is used to partner with other sectors, such as energy providers or engineering companies, to be more resource-efficient and increase their performance. Furthermore, the chemical industry can process a large variety of materials and can play a significant role in advancing IS. However, this will require efforts to standardise streams involved in mutually beneficial exchanges, such as by defining quality standards and enabling new markets (CEFIC, 2020b; Elser and Ulbrich, 2017).

3.2.2 Steel sector profile

The steel sector is involved in 83 exchanges out of the 252 in the database (33%). Traditionally **steel has a strong source profile** providing slag and steam (waste heat) to other sectors. From Appendix A, the steel sector as a source is confirmed with 60 cases in total, prominently covering traditional resources. Table 6 shows that steel as a source primarily enables waste (36 cases) and energy (15 cases). The main sectors involved as sinks for steel streams are cement (C2351), chemicals (various), and other non-ferrous metal sectors (C2445). Overall, the steel sector is involved in waste exchanges, mainly supplying blast furnace slag and coke oven gas. In the cement sector, the use of steel slag has become common practice, while the use of steel streams in the chemicals sector brings new uses for steel residues (Giorgian, 2019; RESLAG project, 2015).

Table 6 Steel sector profile, as a source, has most frequent IS cases with cement, chemicals, and non-ferrous metal production sectors added with the urban district.

Sector	NACE	Waste	Energy	By-product	Water	Total cases
Manufacture of cement	C2351	12	1	0	1	14
Manufacture of other inorganic basic chemicals	C2013	4	5	0	0	9
Other non-ferrous metal production	C2445	4	0	3	0	7
Urban district	NA	1	6	0	0	7
Manufacture of other non-metallic mineral products	C2300	7	0	0	0	7
Construction of roads and motorways	F4211	4	0	0	0	4
Electricity, gas, steam, and air conditioning supply	D35	0	2	0	1	3
Manufacture of coke and refined petroleum products	C19	0	0	2	0	2
Manufacture of articles of concrete, cement, and plaster	C236	2	0	0	0	2
Agriculture, forestry, and fishing	A01	1	0	0	0	1
Construction	F4200	1	0	0	0	1
Manufacture of fertilisers and nitrogen compounds	C2015	0	0	1	0	1
Manufacture of chemicals and chemical products	C20	0	0	0	1	1
Manufacture of industrial gases	C2011	0	1	0	0	1

Total cases		36	15	6	3	60

Table 7 shows the **steel sector as sink** with 23 cases. Steel consumes waste (13 cases) mainly from urban districts (11 cases). Most energy synergies are with energy supply (3 cases). The few by-product synergies are with other EIIs (2 cases) and water again with urban districts. The main sectors involved as a source are urban districts, energy (D35), and cement industries (C2351), together with chemicals (various). Steel is a circular sink for waste steel in other sectors (4 cases), next to accepting waste plastics and home appliances (Appendix A). The increased collection and use of steel scrap promises to play a key role for the sector in the transition to a circular economy (Axelson et al., 2021).

Table 7 Steel sector profile, as sink, has most frequent synergies with urban district, energy supply, and chemicals sectors.

Sector	NACE	Waste	Energy	Water	By-product	Total cases
Urban district	NA	11	0	2	0	13
Electricity, gas, steam, and air conditioning supply	D3500	0	3	0	0	3
Manufacture of chemicals and chemical products	C20	0	1	1	1	3
Manufacture of cement	C2351	0	1	0	1	2
Aluminium production	C2442	1	0	0	0	1
Manufacture of basic metals	C2400	1	0	0	0	1
Total cases		**13**	**5**	**3**	**2**	**23**

According to Table 6 and Table 7, as also summarised in Table 3 for the main EII sectors, the **steel sector** has links with chemicals, cement, and urban districts mainly as a source of useful waste. A typical synergy is the use of steel by-products for construction materials in nearby urban areas. Steel is also a source of valuable waste for the chemicals and cement sectors (RESLAG project, 2015). For cement, the supply of steel slag is a typical synergy, while for chemicals, there are innovative applications that require additional research (Kriskova, 2013). Steel is also a source of energy for chemicals, cement, and cities, enabling heating networks. The energy integration with cement by establishing heating networks is an option highlighted in the EPOS project (EPOS project, 2019a), either as a direct exchange or by developing economies of scale to upgrade the heating profile for power production (Pili et al., 2020).

Thanks to the processing capacity in its furnaces, the sector is a sink for by-products from cement and chemicals. Steel industries not only make use of the energy recovery strategies, material reuse also adds new properties to the steel products (Plastics Europe AISBL, n.d.). The steel sector often utilises urban waste containing steel (World Steel, 2019). Finally, there are links between the steel sector and urban districts for energy to improve district heating (Li et al., 2016; Schweiger et al., 2019) and water cases (Colla et al., 2017; Li et al., 2016; Schweiger et al., 2019), the sector having roles both as a source and sink for synergies.

3.2.3 Cement sector profile

The cement sector is involved in 58 cases of the 252 cases in the database (23%). Cement has a long tradition as a sink for secondary materials, exchanging mostly with steel. Table 8 shows that cement is a resource sink in 47 cases, valorising waste from different industries. Involved sectors are steel (C2410) and energy supply (D35), followed by urban districts and chemicals (C20). Cement is often a sink for furnace slag, fly ash, next to waste plastics (Appendix A). The concept of co-processing waste has been key in cement industries to keep a competitive position and establish sustainable business relationships with other sectors (Güereca et al., 2015).

Table 8 Cement sector profile, as sink, has most frequent IS cases with steel and energy supply sectors added with the urban district.

Sector	NACE	Waste	Energy	By-product	Water	Total cases

Manufacture of basic iron and steel and of ferro-alloys	C2410	12	1	0	1	14
Electricity, gas, steam, and air conditioning supply	D35	4	1	0	0	5
Urban district	NA	3	1	0	1	5
Manufacture of chemicals and chemical products	C20	0	3	1	1	5
Aluminium production	C2442	2	0	1	0	3
Manufacture of paper and paper products	C1711	3	0	0	0	3
Manufacture of food products	C108	1	0	1	0	2
Other non-ferrous metal production	C2445	2	0	0	0	2
Extraction of crude petroleum and natural gas	B6000	1	0	0	0	1
Mining of coal and lignite	B5000	1	0	0	0	1
Manufacture of coke and refined petroleum products	C19	1	0	0	0	1
Waste collection, treatment, and disposal activities; materials recovery	E3800	0	1	0	0	1
Manufacture of other organic basic chemicals	C2014	0	0	1	0	1
Manufacture of pulp, paper, and paperboard	C1710	1	0	0	0	1
Manufacture of basic metals	C2400	1	0	0	0	1
Total cases		**33**	**7**	**4**	**3**	**47**

The higher relevance of the **cement sector as a sink,** as shown in Table 8, may be related to the high capability of energy and material recovery inherent to the manufacturing process of cement. Evidence of this is that as a sink, most of the synergies are related to material recovery based on waste, followed by the energy synergies where the use of alternative fuels is frequent. Such internal capability leaves little space for supplying under-used resources to other industries. However, a main issue of cement is the CO_2 production from non-combustion processes (Naims, 2016). The potential of such abundant underused resource is currently being explored in pilot projects (LEILAC project, 2020).

The profile of the **cement sector as a source** of resources is quite limited, with only 11 cases, as shown in Table 9. The cement sector is a source of energy (5 cases), waste (3 cases), and by-product (3 cases). The main sectors involved are energy supply (D35) and steel (C2410) together with chemicals (C20).

Table 9 Cement sector profile, as source, has most frequent IS cases with the energy supply, steel, and chemicals sectors.

Sector	NACE	Energy	Waste	By-product	Total cases
Electricity, gas, steam, and air conditioning supply	D35	1	0	1	2
Manufacture of basic iron and steel and of ferro-alloys	C2410	1	0	1	2
Manufacture of chemicals and chemical products	C20	2	0	0	2
Manufacture of articles of concrete, cement, and plaster	C236	0	1	1	2
Manufacture of other non-metallic mineral products	C2300	0	1	0	1
Urban district	NA	1	0	0	1
Manufacture of dyes and pigments	C2012	0	1	0	1
Total cases		**5**	**3**	**3**	**11**

According to Table 8 and Table 9, as also summarised in Table 3 for the EIIs, the **cement sector** has links with chemicals, steel, and urban districts in terms of waste, mainly as a sink. Cement has strong links with chemicals enabling waste networks among the sectors (Jassim, 2017; Moreno-Maroto et al., 2017), based on the transformative capacity of both sectors. For this same reason, cement is a sink for waste from steel and urban districts (De Beer et al., 2017). Cement serves as a source and sink of energy, with urban districts mainly using district waste as fuel and providing heating services (IPP, 2013). Finally, in terms of by-products, the sector is a sink for chemicals with potential for CO_2 related synergies (Leeson et al., 2017).

3.2.4 Urban district profile

The urban profile is a collection of exchanges to and from facilities in cities (12% of the total cases). **Urban districts are mostly involved as a source** of resources, supplying waste (16 cases), water (4 cases), and energy (2 cases), as shown in Table 10. The main industrial sectors involved as sinks are steel (C2410), cement (C2351), and chemicals (various). Districts supply waste plastics, waste steel, and discarded home appliances as the most frequent cases.

Table 10 Urban district profile, as source, has most frequent IS cases with steel and cement sectors.

Sector	NACE	Waste	Water	Energy	Total cases
Manufacture of basic iron and steel and of ferro-alloys	C2410	11	2	0	13
Manufacture of cement	C2351	3	1	1	5
Manufacture of chemicals and chemical products	C2000	1	0	0	1
Manufacture of refined petroleum products	C1920	0	0	1	1
Manufacture of coke and refined petroleum products	C19	1	0	0	1
Manufacture of chemicals and chemical products	C20	0	1	0	1
Total cases		**16**	**4**	**2**	**22**

Districts have a limited profile as a sink for resources, as shown in Table 11. However, a typical case relates to energy, where district heating networks integrate waste heat from EIIs. Water synergies are also relevant concerning water treatment infrastructure linked to several industrial facilities (Appendix A).

Attention is drawn to the low number of cases reported for renewable energy synergies despite the fact that such cooperative interactions have the potential to advance wind or solar energy projects, as some studies suggest (Butturi et al., 2019).

Table 11 Urban district profile, as sink, has most frequent IS cases with steel and chemicals sectors.

Sector	NACE	Energy	Water	Waste	Total cases
Manufacture of basic iron and steel and of ferro-alloys	C2410	6	0	1	7
Manufacture of basic pharmaceutical products	C21	1	1	0	2
Manufacture of cement	C2351	1	0	0	1
Total cases		**8**	**1**	**1**	**10**

3.3 Cross-sector profile insights

In this section, insights focus on symbiosis across sectors, using relevant technologies per category and building from cases that are common to the various IS profiles. The second part (3.3.2) presents the sustainability insights following the same categorical approach.

3.3.1 Insights with focus on technologies

This section analysed what technologies are most commonly applied in the above cases. The technologies are addressed at a higher level in terms of stream categories: energy, by-product, waste, and water; they apply to all sectors for both internal optimisations and symbiosis with others.

The by-product and waste categories share the same technologies; the distinction is dictated by legal rather than technical motivations. The technology reviews done in the European IS projects EPOS and SCALER are suitable for gaining insights on technical IS opportunities (EPOS project, 2019b; Azevedo et al., 2019).

Energy technology options

There are three types of energy synergies: heating & cooling, alternative fuels, and electricity. Most of the 70 energy cases have a focus on waste heat symbiosis due to the wide range of temperature profiles in the process industry. Generic technologies to build cross-sector solutions have been highlighted in the EPOS and SCALER projects (Azevedo et al., 2019; EPOS project, 2019b), going from basic pinch point analysis to implementing absorption heat pumps or thermo-compressing processes to improve heating networks. Alternative fuel technologies can be subdivided according to the aggregation state of the stream: solid and non-solid. For solid streams, technology options are grate, fluidised bed, and rotary kiln incinerators. For non-solid waste, there are two general options: fuel cells and combustion engines (EPOS project, 2019b). A key limitation to use alternative fuels is that fuels often have an additional function as raw material that cannot be directly replaced (e.g., coke in steel furnaces). The upgrade of heat streams towards electricity production in co-generation systems is an alternative that takes place depending on the regional electricity market and the on-site capabilities of the sector. Examples of enabling technologies are Organic Ranking cycles and Kalina cycles (EPOS project, 2019b). Renewable electricity can also be sourced from wind turbines or photovoltaic panels at site, cluster, or regional levels (EPOS project, 2019). Figure 4 summarises a non-exhaustive list of technologies. For further details on energy-related IS technology options and models, reference is made to the EPOS tech-watch (EPOS project, 2019b).

By-product and waste
Waste and by-product categories involve 156 cases. In terms of technology options, both categories are grouped as one because, in a circular economy, both can be reused as raw materials in other sectors. A frequent technological challenge in this regard is the purification of the stream and the separation of specific components as often only one substance (such as H_2, CO_2, etc.) or fraction in the stream is valuable for the other industry. Specific technologies and processes for each type of material are required to purify and separate the valuable fractions. Different levels of technological complexity apply depending on the process flexibility and product specifications. Some solutions are directly applicable, e.g., in case of only logistic needs, while others require multi-step mechanical and chemical processing (EPOS project, 2019b; Viganò et al., 2020).

In the database, the most frequent stream is slag from the steel industry. Slag from blast furnaces is used as a cement clinker substitute. Also, the alumina rich slag can be used directly in primary aluminium manufacturing through chemical processing (Azevedo et al., 2019). The mineral properties of slag enable its direct use as raw material, but depending on the end-use, the slag stream may require additional technologies (Azevedo et al., 2019). Streams rich in CO_2 are another key example, where calcium looping is one of the technology options to enable the sequestration of carbon emissions in the entire process industry (EPOS project, 2019b). Depending on the source and the specifications of the CO_2 stream (coal plant, cement kilns, steel furnaces, refineries, etc.), different options to capture and treat CO_2 apply such as pre-combustion integrated gasification combined cycle, vacuum pressure swing absorption (PSA), and amine-based solvent capture (Naims, 2016). It is believed, though, that this is an innovation area of key development and demonstrations in the next decade.

Another example is hydrogen as part of coke oven gas from steel, requiring PSA technology to reach the high levels of purity required in the chemical industry (Azevedo et al., 2019). The list of technologies can be as extensive as the number of streams considered. A case by case evaluation is required to define which technological option suits best the situation for each waste and by-product stream.

Water synergies
Finally, water synergies cover 26 cases. More efficient use of water sources is achievable through better water management, e.g., by recovery of water streams onsite, by integrating technologies for purification and optimal utilisation of available wastewater streams. Here too, separation and purification processes are key. There are mechanical, physicochemical, and biological techniques for the treatment of wastewater. Depending on the type of pollution, a combination of options may be required. In the case of sludge treatment, methanation, liquid waste incineration, and advanced systems for control, monitoring, and management can be considered to use sludge as alternative fuel options. Mechanical separation options range from filtration to electrocoagulation, while physicochemical techniques vary from chemical precipitation to electrolysis. Main biological techniques cover anaerobic filters and anaerobic membrane bioreactors (EPOS project, 2019b).

IS technologies overview based on EPOS tech-watch										
Energy						Waste/by-product		Water		
Heat		Electricity		Fuels		General	Specific	Process treatment		
Recovery	Storage	Thermic	Renewable	Fuel cells	Non-fuel cells	Collection and purifications	Carbon dioxide	Mechanical	Physic-chemical	Biological
•Heat pump •Absorption chiller •Mechanical vapor recompression	•Sensible •Latent	•Stirling engine •Organic Rankine cycle •Kalina cycle	•Crystalline silicon photovoltaic panel •Flat plate solar thermal collector •Flat plate solar thermal collector •Horizontal axis wind turbine •Vertical axis wind turbine	•Proton exchange membrane •Phosphoric acid •Molten carbonate •Solid oxide	•Internal combustion engine •Combined cooling, heat and power •Combined cycle •Microturbine	•Various depending on waste mix and use	•Calcium looping	•Filtration •Electro-coagulation	•Chemical precipitation •Electrolysis	•Anaerobic filters •Anaerobic membrane bioreactors

Figure 4 Overview of technologies for chemicals, steel, and cement sectors synergies.

3.3.2 Insights with focus on sustainability

This section presents critical sustainability aspects from different IS cases grouped per resource category. The insights focus on the environmental part of sustainability in terms of primary resource preservation and emission reduction.

For the **waste** category, circularity is the crucial sustainability driver. Substitution of raw materials such as minerals, metals, or plastics with under-used (by-)products avoids the extraction or use of additional primary resources. Such substitution may require different levels of reprocessing or reformulation, but it is understood that the higher the level of reprocessing, the most likely the sustainability aspects (both environmental and socio-economic) become uncertain (Figge & Thorpe, 2019; Mohammed et al., 2018). Therefore, the sustainability screening focuses on direct synergies that require no or low processing to allow for the synergy to take place.

A typical example has been given above when discussing the valorisation of steel slag in the cement industry (EPOS project, 2019c; Van Oss, 2015). Between 100-300 kg of slag is produced per tonne of steel, of which a significant fraction is used in the cement industry and an increasing fraction in the chemicals sector. Such substitution enables reductions in waste disposal cost and also generates an emission reduction of 0.3-0.6 tonne of CO_2 per tonne of slag substituting raw materials. Another example is the valorisation of coke in steam crackers. Further downstream, the use of waste plastic from industrial or residential sources as raw material for steel and cement industries is a promising raw material substitution with additional gains in energy due to a higher calorific value of the stream compared with traditionally used resources (EPOS project, 2019c). Another option in the waste category is the use of industrial inorganic residues enabling co-product valorisation in mineral and cement industries based on direct substitution (EPOS project, 2019c). Also, from the steel and chemicals sector, sludge and fly ash are potential streams to be used in the cement industry. Finally, urban sludge can be used as input for the cement industry; although it requires pre-treatment, it can substitute both raw materials and fuels. The range of IS cases substituting raw materials with under-used process streams is growing but still varies highly across sectors. The potential rises from 5% to 70% across the sectors such as chemicals, steel, minerals with engineering support (EPOS project, 2019), depending on the availability of supply and demand in the region and non-technical factors such as space available for storage, technological capability, economic conditions, support incentives, and social relevance (Maqbool et al., 2017; Van Eetvelde, 2018). The sustainability gains of valorising waste through industrial symbiosis lies in superior economic performance, lower demand for primary resources, and improved level of business relations in the cluster added with job creation.

For the **by-product** category, the sustainability advantage is similar to the waste category in the case of resource substitution. Often the difference lies in the concentration level of specific substances present in by-product streams. A keystream is CO_2, which is anticipated to become widely reused in a range of applications across industries, going from building blocks in the chemical industry over the use in fertiliser or mineralisation processes (EPOS project, 2019; CarbonNext project, 2018) to sequestration through enhanced oil recovery (EPOS project, 2019c). The potential valorisation and storage of captured CO_2 emissions from industrial processes ranges widely depending on the industry based on the process in place and the available technology options (CarbonNext project, 2018; IOGP, 2019; Naims, 2016). The energy recovery in CO_2 rich streams also plays a role in the sustainability performance of the synergy, as they frequently have high temperature levels. Cement kilns and blast furnaces in the steel sector are important sources that may well fit the chemicals opportunity to develop products with circular market demand (EPOS project, 2019c). In the EPOS project, hubs for upgrading captured CO_2 were proposed (EPOS project, 2019c) with a potential to reduce 20-40% of the treatment costs due to economies of scale. Overall, the sustainability gains of valorising by-products through industrial symbiosis are similar to those for waste streams lowering the demand for primary resources while reducing emissions, and improving the level of business relations in the cluster.

In the **energy** category, the key substitution potential lies in primary energy resources having a final use for heating-cooling networks, electricity generation, and fuel switching. Related to heating networks, there is a potential to recover waste heat in the chemicals, steel, and cement sectors, leading to a reduction of energy consumption of 5-10% at the sector level (EPOS project, 2019d). In terms of alternative fuels (EPOS project, 2019c), savings of around 20-22 GJ per tonne of waste fuel are estimated for chemicals, steel, cement, and urban districts. For the steel industry, this corresponds to savings of 80-150 kWh of electricity per tonne of steel by turning waste heat into electricity (EPOS project, 2019c). The distance between plants remains a critical factor for heating networks (Bütün et al., 2019; EPOS project, 2019c), balancing multi-site optimisation and conversion to electricity or for internal reuse. The sustainability gains of valorising under-used energy streams through industrial symbiosis lie in reaching economic opportunities that are not accessible without partners, unlocking the potential for non-traditional energy sources and developing business relations with additional stakeholders.

Finally, the **water** category refers to water networks that improve industrial water management. Water is a scarce resource, and optimal reuse of wastewater streams is evolving into common practice. By implementing water networks, there is a potential increase in efficiency of 10-50%, avoiding primary water sources (EPOS project, 2019c). In terms of common reuse of water, joint treatment facilities are known to advance the sustainable use of water among companies in an industrial park and in urban-industrial synergies. They create an economy of scale concerning building and operating the plants, generate lower demand on primary water and improve business relations across sectors (EPOS project, 2019c) .

Overall, the sustainability aspects in the IS cases focus on environmental performance. Economic impact estimations are often made, however, there are significant variations among sectors, regions and time periods that make a systematic comparison less suitable for the initial identification phase of IS. Social aspects are also mentioned in terms of potential growth, job creation and the creation of urban-industrial networks and communities. Again, such information is not detailed enough to distinguish between sector profiles, which is the aim of the present paper.

4. Discussion

The discussion of the analytic results presented above is held at three levels. The first-level focus lies on the gaps found in terms of synergies, technologies and sector classification. Secondly, the non-technological aspects of symbiosis projects and their sustainability gains are discussed from a management perspective. In a final section, the learnings are integrated into a method for continuous improvement of IS databases.

4.1 Gap analysis of results

Three types of gaps are identified for enabling a better definition and further facilitation of cross-sector symbiosis in energy-intensive industries: synergy gaps, technology gaps, and sector classification gaps.

Synergy gaps

Table 3 helps to identify missing synergies across sectors at the level of stream categories while recognising the many symbiosis opportunities that are already explored. Still, it is observed that none of the process industry sectors has IS cases related to the use of by-products in urban districts. In terms of symbiosis with communities, most synergies refer to energy or waste streams (EWC code classified), but an apparent lack of urban reuse of industrial by-product streams is observed. This can be explained by the specificity of by-products from industry in the context of urban areas such as residential, commercial, and public facilities (roads, parks, etc.) (Kennedy et al., 2011; Lucertini & Musco, 2020), where a direct use may not be easy to find. Also, urban material streams, broadly categorised as urban waste, lack a valorisation step for potential reuse in industry. A promising option for further exploration is found in electronic waste from urban areas to be valorised in process industries such as chemicals and metal processing sectors (Wyns et al., 2018). Such urban-industrial symbiosis is considered to challenge the ability of cities and industries to join forces in driving the circular economy (European Commission, 2020b; A. SPIRE, 2018; EMF, 2015).

Technological gaps

The technology options presented in the results section show a representative list of existing options per category. However, innovation is challenging new technologies to emerge next to extending or improving the use of current technologies in order to tackle climate and resource neutrality. New tools and technologies to support IS cover energy grid optimisation and local clustering of renewable sources, as suggested in the EPOS project (EPOS project, 2019b). Grid optimisation refers to energy flexibility, buffering, and storage options, next to the implementation of digital energy signals. Local clustering refers to the generation and valorisation of renewable energy through joint investments. Typical examples are wind and solar energy to increase the availability of zero-carbon energy in a region, but hydrogen technologies and infrastructure also grow in importance and require local (public-)private partnerships to renovate and stimulate the hydrogen economy. Such options open the symbiosis scope to multiple sectors and invite service providers to facilitate joint action at industrial sites or even at a regional level. Synergies using such technologies are often not identified as IS cases due to issues to quantify the benefits for each party. To overcome this miss-out, a recent article on the technical viability of synergies proposes a three-step assessment method: compliance, characterisation, and feasibility (Dias et al., 2020). The methodology can be used to develop the technical aspects that characterise synergies and to evaluate the mutual sustainability gains resulting from the cases. Next to win-win allocation issues, other reasons for missing technologies as IS enablers are the critical time dependency and the complexity of many synergies. Here, however, the application of systems dynamics to IS cases is promising in its ability to open new opportunities for energy and waste technologies. Maqbool et al. (2019) investigated the dynamics and flexibility of wind energy integration using agent-based modelling to propose effective incentives at a policy level. Using a site-level approach, Norbert et al. (2020) developed systems dynamics frameworks for steel plants, enabling dynamic IS simulations for assessing environmental and economic benefits.

Classification gaps

Lastly, the use of NACE as a framework for IS classification shows advantages and disadvantages. Main advantages are the definition of the sectors in standard terms to connect with statistical databases such as EUROSTAT and get direct insights. The main disadvantage is the fixed layers of specificity that are not suitable for all cases or sectors. In the case of the steel sector, for example, the highest level of specificity includes the iron ore industry. Another observation is that the chemicals sector is difficult to categorise due to its diversity and the interconnectivity of many different sub-sectors. In this article, the base was taken from CEFIC (CEFIC, 2020a) added with oil refining since it is closely associated with petrochemical processing activities, processing of plastics, and others included in the four NACE codes chosen (C19, C20, C21, C22). Handling such issues requires developing a higher level of specificity for the industries in the cases collected, such that they can be easily adapted and grouped in sectors as required.

4.2 IS management and sustainability

The possibility to sustainably develop industrial symbiosis depends on internal and external factors that are often more complex than technology or engineering solutions. For such complexity, cluster management options gain priority. Before discussing the LESTS management approach for IS (Maqbool et al., 2017; Van Eetvelde et al., 2005), the internal and external influences are described in this section.

Internal conditions for successful IS depend on many aspects such as a lead person in the company or a key entity in a cluster, available resources, existing infrastructure, economic incentives, technology pathways or breakthroughs, multi-party agreements, and many more. They need to be critically integrated into the sustainability assessment of the symbiosis in order to ensure that new synergies deliver socio-environmental performance next to mutual economic benefits.

External conditions refer to the potential to trigger rebound effects, for instance, due to the availability of competing materials for substitution or the abundance of traditional fossil fuel inputs (Sadik-Zada & Gatto, 2020). The rebound can be generated by the abundance or scarcity of alternative resources in terms of quantity or quality. This promotes or fails the full replacement of a primary resource and generates additional production/consumption along with an added environmental impact. A similar rebound effect can be triggered when secondary resources have lower or higher prices than the current market offers, which stimulates a higher level of consumption, again with a significant impact on the environmental gains (Figge & Thorpe, 2019; Zink & Geyer, 2017).

Both internal and external conditions need an evaluation per specific IS case to clarify the economic, environmental, and social benefits. Such a multi-level approach cannot be avoided in industrial symbiosis projects, but it faces the problem of fragmenting IS potential at specific levels, in casu the partnership, the entity/company involved, and the particular resource flow (Kerdlap et al., 2020; Maqbool et al., 2017).

A central challenge in addressing non-technological factors is their dependency on contextual elements, leading to a virtually unlimited range of drivers and pitfalls. At the level of sectors, it is useful to clarify specific domains or dimensions to map the motives and barriers for IS initiatives. A framework resulting from cluster management research is the LESTS approach (Maqbool et al., 2017; Van Eetvelde et al., 2005) used to map legal, economic, spatial, technological, and social factors. Organised by resource category and sector profile, relevant factors can be registered to bring non-technical insights to the case in a systematic way. Any factor can drive or hamper a symbiosis option. A hampering legal factor for a specific under-used resource stream could be the complicated permit system for sending the resource to another legal entity. However, a legal driving factor could be the compliance with regional legislation to build a pilot for a carbon-neutral process or to receive carbon credits in cap and trade schemes such as EU-ETS (European Commission, 2015). A typical economic driver is a local or regional subsidy scheme but most often it is merely the profit gained from the IS optimisation. A spatial factor can be related to urban or regional planning but also to logistic availabilities of infrastructure such as storage facilities, which may stop or push synergies forward. Technological factors refer to the operational strategy and procedures in place in a company or city, e.g., towards recycling of critical materials. Finally, the social factors imply the interaction and trust among the parties within the industrial cluster but also include direct and indirect benefits to nearby communities. These can be measured in jobs or economic growth, in improved public health or general well-being. Communication and stakeholder engagement are fundamental social factors. The LESTS framework has proven to enable IS insights beyond technology or stream optimisation and allows us to build a more holistic database design in section 4.3. The LESTS information gathering can be organised in a matrix, as proposed in Table 12 illustrated with a simple example of single factors.

Table 12 LESTS factors enable the identification and management of non-technical factors. An example for a typical case is provided with ID 1.

Case ID	LESTS	Factor	Effect for the case (quantitative or qualitative)

1	Legal	Permit requirement	Time/effort spent to acquire permits for symbiosis
1	Economical	Rate of return	Enable negotiation among partners
1	Spatial	Space for new infrastructure	Enable initial feasibility of the project
1	Technology management	Expertise on-site	Time/effort spent to acquire permits for symbiosis
1	Social	Readiness to collaborate	Inclination to trust a partnership and enter the symbiosis clusters, including information flows and space for interaction

The LESTS matrix can also be used as a tool for technology appropriation (Carroll, 2004), taking into account a panoramic assessment of the cluster and region to implement IS solutions. A critical factor for such solutions is the level of uncertainty associated with new technologies that may lead to unforeseen barriers. For such cases, the appropriation of technology may play a prominent role in clarifying the risks and opportunities involved in any IS project. Further research in this area can lead to the design and adoption of pilot technologies under the umbrella of the circular economy.

4.3 IS case-base framework

A further reflection on the methodology used in this article leads to a more general framework to develop IS databases, as shown in Figure 5. The IS case-base framework is envisioned as a continuous improvement cycle based on the Deming management cycle (Deming, 1982; Garza-Reyes et al., 2018), starting from setting the goals of the database to select IS schemes and running until all stakeholders obtain expected insights. The concept of an IS case-base refers thus to the product of such a cycle.

The cycle towards an IS case-base describes and summarises the learnings and recommendations obtained in working with most recent databases from successful EU projects focusing on main EIIs.

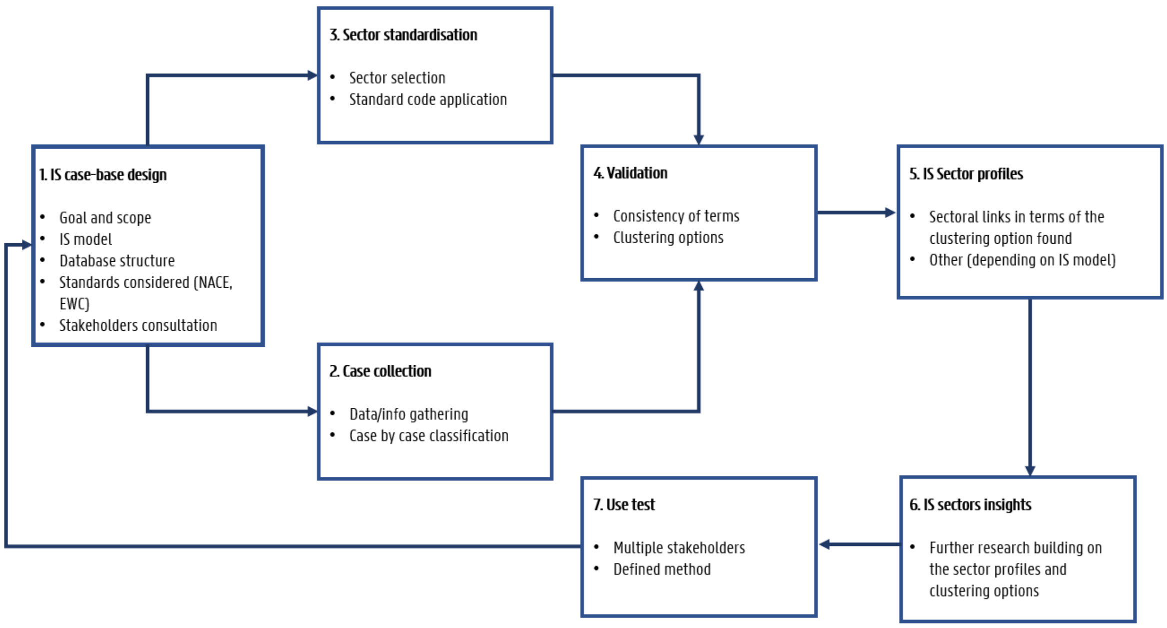

Figure 5 IS case-base framework: The improvement cycle reveals critical aspects for designing and collecting IS databases.

The first step is a structural IS case-base design. It has five elements. The *goal* & *scope* is defined by the stakeholders expected to use the case collection. The next element is the IS *model* suitable to fulfil the expectations, including the selection criteria and case characterisation. The database *structure* is then defined by the IS model and clarifies the domains where *standards* play a role (sector, waste, LESTS aspects, etc.). The IS case-base design can be expanded to have additional elements depending on the goal & scope, the initial *consultation of stakeholders*, or the results of use tests in the final step of the cycle. As an illustration of this structural design, it is argued that the database in the MAESTRI project aimed to facilitate the identification of IS with a straightforward input/output approach. The objective was to promote IS solutions by mimicking existing cases to extend their replication potential (Benedetti et al., 2017). Comparing with MAESTRI, the EPOS collection was developed within the scope of specific industrial clusters and technologies in Europe, but aimed at wider replication within the region. In a similar way, SCALER developed 'synergy types' or semi-generic synergies that aim for replication. Both projects provide a techno-economic assessment together with an environmental appraisal.

In the next step, the IS data collection and standardisation per sector is covered. In this step, the information is gathered systematically, guided by the IS model selected to cover all relevant aspects. When participants and other elements in a case are defined according to the standard codes or classification agreed upon, sector standardisation is done. In the present article, the NACE codes and the EWC were taken into account as a typical case.

The validation process starts when the collected data are revised in terms of input consistency and clustering options (resource category, region, etc.). This should enable different levels of analysis and insight. Application of data clustering techniques (Dunkelberg et al., 2019) and stream ontologies are part of this step (Nooij, 2014; Gruber, 1995). In the present article, the categories were defined by inspection according to references in the literature; for more sophisticated techniques, a higher amount of data is required.

Then IS sectors profiles are defined aligned with the categories and clustering options in the case-base, focusing on links among sectors and the visualisation of results. In this article, the IS sector profiles referred to the overview of participants in synergy and the type of streams that they shared under standard classifications.

The IS insights refer to a further investigation of crucial factors defining the sector profiles. In this article, the IS insights consisted of further investigation on the cross-sector profiles, the technologies involved, and sustainability aspects based on the IS sector profiles obtained from the case-base.

The final step is testing the use of the database with the stakeholders. This step requires the design of a test method that guarantees valuable feedback from all the stakeholders. Such feedback is expected to re-start the cycle by improving some aspects of the IS case-base, for example, the standards considered or the expansion of the IS model.

5. Conclusion

The article provides a documented analysis of current databases and sector profiles for IS, added with an unprecedented framework to develop a case-base for IS in the interface of the public and private domain. A method to describe sectoral profiles for industrial symbiosis is proposed, using existing open-source databases from IS innovation projects funded by the European Commission and considering the latest research on IS databases. By applying the method, IS profiles and insights were presented for key industrial sectors in the context of climate change and the circular economy. Moreover, the method was extended into a framework to build and improve IS databases, derived from the learnings gathered throughout the process, from the initial database compilation to final discussions regarding sectoral insights on technologies and sustainable improvement. The framework considers the need for common goals and stakeholder diversity in the initial design of the IS case-base. This approach is oriented towards sector associations and policymakers due to its relevance to various policy domains requiring joint efforts, going beyond a single industrial site and even sector boundaries.

Framed by today's changing policy landscape, EIIs seek to transition towards a circular economy in Europe. There are several pathways to explore, cross-sectorial symbiosis potential being one of them. An extensive analysis of 252 synergies in place has allowed to develop a methodology for building IS profiles for the chemicals, steel, and cement sector. Waste, energy, by-product, and water were defined as the most prevalent streams being exchanged.

In this paper, each sector acts as a source and sink of resources. Chemicals as a resource sink primarily enables energy and waste synergies, while as a source, the sector enables primarily by-products and energy synergies. As expected, the chemical sector has the highest number of partnering sectors due to its wide range of applications. The steel sector mostly has a source role (72% of its cases) to build waste and energy synergies, and as a sink, the sector also primarily enables waste and energy synergies. In contrast, the cement sector tends to predominantly act as a sink (78% of its cases) developing waste synergies, while as a source, the sector mostly enables energy and waste synergies. Finally, the synergies with urban entities are integrated into an urban district profile for the EIIs. Districts tend to be a source for waste synergies (69% of the cases) with the main EIIs, while as a sink, they enable energy synergies with other sectors (mainly steel).

Building from the IS sector profiles, three focal insights were presented: typical synergies among sectors and urban districts, IS technologies common to all sectors, and sustainability insights drawn from IS cases. The technology insights cover a collection of technologies for energy, waste, by-product, and water synergies. The sustainability insights include an appraisal of the environmental gains for different resource categories and the need for assessing synergies at multiple levels due to the relevance of local non-technical factors.

Further research is encouraged to design case-bases that consider geospatial aspects such as cluster and site locations involving urban districts. Such approach could facilitate the identification and assessment of urban industrial symbiosis in specific regions.

Finally, the identification of new IS cases depends on the IS case-base design, particularly in the IS model selected. Further research on the extension of IS models (e.g., considering new shared services or technologies) can uncover unprecedented synergies to face the present economic and socio-environmental challenges in the transition towards a net-zero, circular economy.

Appendix A. Supplementary data

Table 13 shows the first 10 cases of the collection.

Table 13 IS case collection.

#	Stream class	NACE (source)	NACE name (source)	NACE (sink)	NACE name (sink)	Stream description	Final use	References
1	energy	C2442	Aluminium production	C2011	Manufacture of industrial gases	electricity	electricity	Golev et al., 2014
2	waste	C2442	Aluminium production	C2410	Manufacture of basic iron and steel and of ferro-alloys	red mud	raw material	Dong et al., 2014
3	waste	C2442	Aluminium production	C2351	Manufacture of cement	red mud	raw material	Beers et al., 2007
4	by-product	C2442	Aluminium production	C2351	Manufacture of cement	silica fume	raw material	Golev et al., 2014
5	waste	C2442	Aluminium production	C2351	Manufacture of cement	slag	raw material	Li et al., 2015
6	by-product	C2370	Cutting, shaping, and finishing of stone	C2013	Manufacture of other inorganic basic chemicals	ammonium chloride solution	raw material	Dong et al., 2014

7	by-product	C2370	Cutting, shaping, and finishing of stone	C2012	Manufacture of dyes and pigments	ammonium chloride solution	raw material	Dong et al., 2014
8	waste	C1101	Distilling, rectifying, and blending of spirits	C2015	Manufacture of fertilisers and nitrogen compounds	vinasse	raw material	Yu et al., 2015
9	waste	C1101	Distilling, rectifying, and blending of spirits	C2015	Manufacture of fertilisers and nitrogen compounds	alcohol residue	raw material	Zhu et al. 2007
10	energy	D35	Electricity, gas, steam, and air conditioning supply	C19	Manufacture of coke and refined petroleum products	steam and demineralised water	heating / cooling	Notarnicola et al., 2016

The full table is available in the following as supplementary data.

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Author contributions

Francisco Mendez-Alva: conceptualisation, methodology development, writing original draft, data collection & curation, visualisation. Hélène Cervo: data curation and visualization, investigation, writing-review, and edition. Gorazd Krese: conceptualisation, investigation, writing-review, and edition. Greet Van Eetvelde: ideation, supervision, full writing review and edition, funding acquisition.

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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