DIGITAL PLATFORMS FOR INDUSTRIAL SYMBIOSIS

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Digital Platforms for Industrial Symbiosis

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ABSTRACT

Industrial symbiosis contributes to the realisation of a circular economy where underutilised assets are shared among different companies and the residual outputs from one industry are used as feedstock for the production processes of other industries. While digital platforms have the potential to facilitate the exchange of excess resources in industrial symbiosis networks, existing platforms have not been very successful hitherto. This research empirically investigates the barriers to industrial symbiosis and how digital platforms (fail to) address them. Qualitative, semi-structured interviews were conducted with eleven prospective platform providers based in Norwegian industrial parks, and two platform developers and one provider in the Netherlands. Results show that the uptake of platform-enabled industrial symbiosis is still hampered by limited commitment to sustainability, a lack of cooperation and information sharing, as well as technical and economic barriers. Platform design only partially solves the challenges specific to matchmaking platforms that facilitate the identification and exploitation of synergy opportunities.

KEYWORDS: Barriers Circular Economy, Digital Platform, Industrial Symbiosis, Platform Design

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The circular economy – an economic system that eliminates waste in production and consumption processes by reducing, reusing, and recycling products and materials – is receiving increasing attention from academics and policymakers alike (Andersen, 2007; Kirchherr *et al.*, 2018). While the industrial sector is regarded as a major source of environmental degradation, industry is expected to play a key role in the transition to a circular economy. At a micro-level, single companies can engage with the circular economy by developing innovative business models (*e.g.* based on sharing or reuse), and adopting eco-design strategies and cleaner production processes. At a meso-level, a circular economy involves inter-actor cooperation in industrial networks and symbiotic relationships that deliver economic, social, and environmental gains (de Jesus *et al.*, 2018; Ghisellini *et al.*, 2016).

'Industrial Symbiosis' (IS), a sub-field of industrial ecology, entails the sharing of underutilised assets (*e.g.* machines, vehicles, infrastructures, personnel, expertise, storage space) among firms and the exchange of residual outputs (materials, by-products, energy or waste) from one firm to be used as feedstock for the production processes of other firms (Chertow, 2000; Walls, Paquin, 2015). IS often requires cooperation among businesses in unrelated industries and benefits from the geographical proximity of companies, which are usually located in (eco)industrial parks and clusters (Benedict *et al.*, 2018; Yeo *et al.*, 2019). The implementation of symbiotic relationships can lead to the creation of a so-called "eco-innovative *milieu*" and a favourable environment for the emergence of eco-innovation dynamics (Kasmi, 2018).

The digitalisation of industry may offer new opportunities to achieve a circular economy through IS (Antikainen *et al.*, 2018; Tseng *et al.*, 2018). Information and communication technologies (ICT) make it possible to monitor and track the availability, quality, and location of material and energy flows through manufacturing processes (Antikainen *et al.*, 2018). Based on these data, digital platforms can facilitate the identification of potential synergies and the interaction between firms by supporting the exchange of (real-time) information and matching resource buyers and suppliers (Benedict *et al.*, 2018; Kosmol, Leyh, 2020). Despite the benefits of using digital platforms to enable IS, their application in the industry is not very successful hitherto. Existing platforms lack crucial IS-related services or have failed to reach a critical mass of users (Benedict *et al.*, 2018). Yet there is a paucity of research examining how IS platforms can be designed to overcome the existing barriers to IS (Benedict *et al.*, 2018; Kosmol, Leyh, 2020). Our study sets out to investigate how digital platforms can address the barriers to IS. The study extends current knowledge by empirically exploring both perceived and actual barriers to (platform-enabled) IS, uncovering best

(design) practices and providing actionable recommendations to build effective digital platforms for IS.

The paper is organised as follows. Section 2 introduces the concept of IS and explains how digital platforms may facilitate the sharing of idle assets and waste-to-resource exchanges among different industrial actors located in a business park. This is followed by a description of the design of digital platforms for IS and their limitations. Section 3 describes the qualitative approach adopted in the research to collect and analyse data of IS platform developers and prospective providers in two country contexts (Norway and the Netherlands). Section 4 presents the empirical results regarding the barriers to (platform-enabled) IS and Section 5 concerns the design criteria used to build a viable IS platform. Section 6 discusses the main findings of the study. We conclude in Section 7 with a summary of the key challenges to the wider uptake of digital platforms for IS.

Digital Platforms for Industrial Symbiosis

Industrial Symbiosis (IS) entails the development of interfirm cooperation networks that aim to achieve economic, social, and environmental benefits through the sharing and exchange of excess resources (de Jesus *et al.*, 2018; Ghisellini *et al.*, 2016). Over the years, IS has expanded its scope from purely physical material and energy transactions to more sophisticated forms of cross-organisational cooperation that relies on the exchange of knowledge, information, and expertise to foster eco-innovation and long-term cultural change (Lombardi, Laybourn, 2012; Yeo *et al.*, 2019).

Barriers to Industrial Symbiosis and the Role of Digital Platforms

Although research on IS has grown notably in the last two decades and its economic (*e.g.* lower costs), social (*e.g.* job creation), and environmental (*e.g.* reduced waste and emissions) benefits are well understood, the concept has hardly been implemented in practice (Benedict *et al.*, 2018; Fraccascia, Yazan, 2018; Maqbool *et al.*, 2018). Golev *et al.* (2014) identified seven categories of barriers (and enablers) to IS, which include companies' *commitment to sustainability*, existing environmental *regulations*, (a lack of) *community* awareness and *cooperation* between industries located in the same area, *information sharing* (*i.e.* the availability of data on waste streams and the material/water/energy requirements of local industries), and the *technical* and *economic* feasibility of synergistic transactions. Recent literature review studies provide

more extensive and granular lists of barriers, challenges, enablers and drivers to IS (see Domenech *et al.*, 2019; Henriques *et al.*, 2021; Neves *et al.*, 2019; Södergren, Palm, 2021), but often group them in macro-categories of technical and non-technical barriers/enablers to IS similar to those developed by Golev *et al.* (2014).

Orchestrating IS inter-firm cooperation is a complex task, which is increasingly supported by ICT (Grant *et al.*, 2010; Maqbool *et al.*, 2018; Yeo *et al.*, 2019). IS tools include online marketplaces, databases, social network applications and knowledge repositories (van Capelleveen *et al.*, 2018) that support the development of IS projects in the process of synergy identification, symbiosis assessment (*i.e.* the evaluation of the benefits and challenges associated with IS activities), removal of existing barriers, implementation of transactions, and the follow up steps of documentation and review (Bonnet *et al.*, 2016; Grant *et al.*, 2010; Maqbool *et al.*, 2018).

The literature on IS tools indicates a general trend from databases with a focus on data collection to digital platforms that work as 'ecosystem enablers' (Benedict *et al.*, 2018). Digital platforms have recently been recognised as a means to facilitate a circular economy: they can serve as a market for excess capacity (*e.g.* sharing access, resell and trade products, components and material); can be used to operate product-service systems, thereby facilitating maintenance and repair activities; and can empower people to share knowledge and co-create products and services for a circular economy (*e.g.* crowd-sourced repair kits) (Konietzko *et al.*, 2019). In the context of IS, digital platforms are mostly developed to share information, facilitate open electronic markets, and provide additional IS-related services that enhance cooperation, participation and community awareness (Benedict *et al.*, 2018; van Capelleveen *et al.*, 2018; Kosmol, Leyh, 2020). SHAREBOX[1] is a prime example of a digital platform that functions both as a management tool for IS and a marketplace for trading industrial waste and by-products. The platform enables companies to record their excess resources or those needed and facilitates matching supply and demand by means of AI-powered algorithms. Specialised modules help users evaluate transaction opportunities, enter into technical discussions, bilaterally negotiate deals, and subsequently track, manage, and report on the synergies created.

1. Sharebox: Secure Sharing. http://sharebox-project.eu/

Platform Design and Challenges to the Implementation of a Platform-Enabled Industrial Symbiosis

To date, however, the diffusion of digital platforms for IS remains limited and most of the existing IS platforms face difficulties in remaining operational (Grant *et al.*, 2010; Maqbool *et al.*, 2018). Benedict *et al.* (2018) identified four main challenges to the successful implementation of IS platforms. The first one relates to the availability, quality, and compatibility of data. Not all data necessary to enable synergistic transactions are proactively provided by companies as they often concern confidential information. IS platforms also fail to facilitate manual data handling or exchange due to a lack of interoperability between different systems (*e.g.* LCA databases, standardised waste catalogues). Moreover, expert knowledge is required to interpret large amounts of heterogeneous data (*e.g.* technical, environmental, organisational) required to identify and assess IS synergy opportunities. Second, the social aspects of IS – willingness, trust, cooperation, and reciprocity – are often neglected in favour of technical feasibility and economic efficiency. Third, the functionalities of current IS platforms usually reach no further than serving as a digital marketplace supporting the initial step of synergies identification (Kosmol, Leyh, 2020), and they often target only one type of waste/resource stream (Bonnet *et al.*, 2016). Finally, many IS platforms are difficult to access by other industrial parks beyond a specific project community (Kosmol, Leyh, 2020) and the level of awareness among potential users is usually low. As a result, most IS platforms fall short when it comes to attracting new participants over time and become static networks of resource sharing.

Additional challenges specifically apply to digital platforms operating as online marketplaces that facilitate the identification of synergies for waste-to-resource exchanges or underutilised asset sharing. Matchmaking platforms are meant to reduce informational barriers among companies, *e.g.* making firms aware that a certain waste stream or asset is available or in demand, and lower transaction costs connected with the search for, negotiation, and monitoring of symbiotic collaborations (Fraccascia, Yazan, 2018). However, two-sided market platforms need to overcome the so called 'chicken-and-egg problem' – to attract a sufficient number of suppliers they require a sufficient number of buyers, and *vice versa* – and reach a critical mass of users to reap the benefits of positive (direct and indirect) network effects and effectively facilitate matches (Gawer, Cusumano, 2014; Piscicelli *et al.*, 2018).

To address the limitations of existing digital platforms for IS, Benedict *et al.* (2018) and Kosmol and Leyh (2020) proposed a set of design guidelines with a focus on accessibility issues, platform customisation, and governance

mechanisms. Similarly, Bonnet *et al.* (2016) elaborated a list of recommended functionalities for an ideal IS platform. Contributions of a more technical nature used agent-based modelling to simulate the impact of specific platform design choices (*i.e.* sharing sensitive *vs* non-sensitive information) on the economic and environmental performances of IS exchanges (Fraccascia, Yazan, 2018), or developed a hypothetical system architecture of a collaboration platform for IS (Raabe *et al.*, 2017). Nevertheless, the platform features and design requirements available in the literature remain scarce and of a theoretical nature (Kosmol, Leyh, 2020), while there is a lack of empirical studies that examine how operational platforms are designed to overcome the barriers to IS.

Methodology

This study adopted a qualitative approach to empirically identify the barriers to (platform-enabled) IS and examine the design characteristics of existing digital platforms that facilitate the exchange of waste/by-products and the sharing of underutilised assets. Such platforms are generally deployed in 'facilitated networks', where a third-party intermediary coordinates the IS activity, and 'planned networks' in specific industrial areas, where companies benefit from shared infrastructures and services and the coordination/promotion of IS exchanges is provided by *e.g.* the cluster manager of an industrial park (Domenech *et al.*, 2019). A purposive sampling method (Robinson, 2014) was used to select suitable cases for the analysis. To explore IS barriers, we selected Norwegian industrial park organisations as prospective platform providers, since industrial park organisations often offer IS platforms as a service to their tenant companies. The choice was motivated by the absence of active IS platforms in the country (at the time the study was conducted), despite a favourable environment for the development of IS relationships in terms of political, economic, social and environmental supporting conditions (Neves *et al.*, 2019). We reached out to Norwegian organisations operating in industrial parks with a substantial number of firms, since they have the potential network that is relevant for the creation of an IS platform. Organisations that manifested their ambitions concerning the circular economy on their corporate website or in newspapers were prioritised, as they were deemed (more) knowledgeable about the topic under investigation. From a list of fifteen industrial parks that were contacted by successive email and phone calls, nine industrial park organisations eventually agreed to participate in the study (Table 1).

Table 1 – Norwegian Industrial Park Organisations (prospective IS platform providers)

	No.	Industrial Park Organisation (O)	Characteristics
O1	1	Mo Industripark (MIP), Mo I Rana	Located in Northern Norway, it is one of the oldest and largest industrial parks in the country. It hosts more than 100 companies over an area of 260 hectares. Most companies are active in the metal and mining industry. MIP aims to become a world-class green industrial park, with a focus on energy efficiency, recycling and emissions reduction. Material and energy IS exchanges are already operative in the industrial park.
O2	2	Thams Klyngen and Næringshagen i Orkdalsregionen, Orkanger	Established in 2018, the industrial cluster has the ambition to promote innovation and collaboration among the cluster's participants to lower emissions, increase energy efficiency and achieve a higher degree of circularity. Companies are mainly in the food, offshore and process industry. Existing IS projects focus on the exchange of by-products and they are seeking for further IS opportunities.
O3	1	Kongsberg Teknologipark (KTP), Kongsberg	Originally established in 1814, the industrial park counts about 60 tenant companies active in different sectors, such as defence and aerospace technology. KTP has the goal to reduce energy consumption and increase energy efficiency and recycling rates. There are no formal IS collaborations in place beyond the redistribution of surplus heat from machines/processes and occasional exchanges of personnel.
O4	2	Skogmo Industripark (SIP), Overhalla	Established in 2006, the industrial park consists of 54 companies that operate mainly in industrial production and transport. SIP offers sustainability and digital transformation programmes, as well as climate accounting services to its member companies. SIP also facilitates the sharing of assets (*e.g.* carsharing) and competences across its tenant companies.
O5	1	Proneo, Verdal	Founded in 2007, Proneo provides innovation and sustainability support services to companies located in different industrial parks including Verdal Industrial Park (VIP) and its 190 tenant companies, which mostly operate in the mineral, construction and food industry. VIP does not have a strong focus on sustainability and there are no active IS projects in the area beyond casual sharing of production facilities and personnel among some companies.

	No.	Industrial Park Organisation (O)	Characteristics
O6	1	Industrial Green Tech (IGT), Herøya	Founded in 2019, IGT serves around 100 companies located in 3 industrial networks and active in the process industry, mostly for petrochemicals, metal and cement. IGT's ambition is to become the world's first climate-positive industrial region, with projects in the area of industrial digitalisation, circular economy (*e.g.* reuse and recycling of materials and industrial packaging) and emissions reduction.
O7	1	Sintef Manufacturing/ Catapult Centre (SM), Raufoss	SM offers industrial research and consulting services, as well as facilities and equipment that companies can use for testing new production technologies. SM leads the NCE (Norwegian Centre of Expertise) Raufoss industrial cluster, which was created in 2006 and involves 17 companies active in the automotive, defence and electronics industries. The goal of NCE Raufoss is to enhance sustainable innovation and establish a collaborative environment between participating companies. There is no active IS project in the cluster.
O8	1	Norwegian Center of Circular Economy (NCCE), Friedrikstad and Øra Industripark	NCCE was created in 2016 by two network organisations and their 45 member companies. The aim of NCCE is to provide facilities and consultancy services for companies interested in new circular business opportunities, *e.g.* reuse of industrial waste or residual products. NCCE has the ambition to build a digital marketplace to facilitate IS exchanges, but this is still in the ideation phase.
O9	1	Arctic Cluster Team (ACT), Mo I Rana	Established in 2017, the cluster now counts 60 firms and aims to support a sustainable transformation of the process industry through innovation, digitalisation and collaboration. IS is one of the themes the cluster works with: ACT developed a project to build a digital lab for identifying IS synergies in the industrial ecosystem of Mo Industripark. The project ended as it failed to attract governmental funding.

To examine the design characteristics of active IS platforms, we contacted the developers of two digital platforms that were already operational in the Netherlands: Floow2 – who created the IS platform 'Parksharing' – and Stichting InduSym. We also included in the sample (Table 2) Solaris Parkmanagement, a Dutch organisation that manages more than 20 industrial parks in the country and is offering the Parksharing platform as a (sustainability related) service to the tenant firms of 6 of the business parks it operates. Norway and the Netherlands provide for a pertinent empirical

comparison: the two countries have formally committed to achieving ambitious circular economy targets and support IS, but their number of active IS initiatives remains rather limited. The development of IS in both countries is characterised by a bottom-up business driven approach (Domenech *et al.*, 2019), led by private companies and business parks. Nevertheless, digital platforms for IS are currently operated by some Dutch industrial park organisations, whereas they are completely absent in the Norwegian context.

***Table 2* – Dutch Platform Developers/Providers**

	No.	Platform Developer (D)/Provider (P)
D1	1	Floow2 Parksharing, Oisterwijk
D2	1	Stichting InduSym, Beek en Donk
P3	1	Solaris Parkmanagement, Nieuwkuijk

The interviews were conducted between December 2019 and April 2020, when possible in person at the organisations' premises. However, most of them took place online due to travel limitations related to the COVID-19 outbreak in Europe at the time. Interviews were carried out with one interviewee except for O2 and O4, who provided two interviewees. The interviews were semi-structured (Bryman, 2016). The many follow-up questions resulted in extensive interview sessions that took one to one and a half hours. All interviews were conducted in English, digitally recorded and transcribed verbatim. Data were analysed with the help of the NVivo Qualitative Data Analysis Software using thematic analysis and a hybrid approach of inductive (data-driven) and deductive (theory-driven) coding (Fereday, Muir-Cochrane, 2006). Informed consent was obtained prior to each interview.

To structure the conversations, we used an interview guide adapted to the two groups of participants (*i.e.* prospective IS platform providers in Norway and IS platform developers/providers in the Netherlands) (see Appendix). The order of the questions posed to the interviewees was flexible, but eventually all questions from the guide were covered. As the interviews in Norway were conducted with representatives of organisations who had no direct experience with platform-enabled IS, the interview was divided into two parts. The first part contained questions about the possible barriers and enablers to establish IS collaborations in the organisation's industrial park, following the aforementioned seven barriers to IS identified by Golev *et al.* (2014). Subsequently, the interviewer explained the concept of a digital platform for IS. The second part contained questions about the perceived barriers and benefits of using an IS platform and proposed design requirements. Conversely, the interviews conducted in the Netherlands focused on

the platform features and design criteria relevant for the establishment and operation of IS platforms.

Barriers to (Platform-Enabled) Industrial Symbiosis in Norwegian Industrial Parks

The seven categories of barriers *viz.* enablers to IS identified by Golev *et al.* (2014) are: companies' commitment to sustainability, existing environmental regulations, (a lack of) community awareness and cooperation between industries located in the same area, information sharing, and the technical and economic feasibility of synergistic transactions. The interviewees indicated that five out of the seven were seen as barriers: *a lack of commitment to sustainability*, *a lack of cooperation*, *informational barriers*, *technical barriers* and *economic barriers*. According to them, the use of an IS platform would only partly overcome the existing barriers to IS.

Lack of Commitment to Sustainability

Many interviewees explained that a large barrier to IS is the ready availability of (virgin) resources and the little incentive to reduce environmental impact. As a consequence, companies have traditionally focused on short-term goals and profit maximisation without the need for interfirm collaboration. Some respondents further explained that sustainability is usually regarded by managers as a side issue, if not a loss-making business: "*I think the main challenge, same as in other environmental innovation projects, is [that it's] the society that's gaining: it's not one of the actors involved […] that gains from us building these ecosystems [read: IS networks]*" (O9). Projects like IS are often not initiated or actively considered because companies do not see it as business opportunities, but as "*only green*" (O7).

Lack of Cooperation

According to O6, innovation had been very fragmented at the companies in her cluster: "*They have innovated a lot, but each of them in their separate companies. So, the tradition, the culture for sharing has not been here.*" For example, $O4_1$ discussed a project they initiated in the industrial park to introduce the concept of asset sharing: the organisation bought a car that can be reserved by the firms in the area. The booking fee is an "*extremely low amount, […] the payment is only for covering the costs.*" The project, launched more than a month before the interview, was received with enthusiasm by all firms, but

the car was still not booked. The two interviewees agreed about the reason: the habit of sharing is "*quite uncommon*" ($O4_2$) in their industrial park and it is hard to change the way people think: "*There has to be, let's say, a mental change. […] people are used to have [their own] car available. Now they have to check if it's available in our booking system*."

The issue of mutual trust also came up when discussing the barriers to IS in Norwegian industrial parks. $O2_1$ emphasised its importance: "*The biggest barrier maybe is trust: lack of trust and lack of knowledge about the neighbour. They don't know what the neighbours do. The biggest barrier […] is that they don't know each other and they are a bit afraid of new things*."

Moreover, some interviewees pointed out that firms might be protective about sharing data on production streams, which might be a problem for identifying matches. O9 experienced this in a project launched in an oil and gas cluster, where they tried to share assets among firms: "*… but they were so competitive that they couldn't be open about these things [data on available assets]. We were trying to make the spreadsheets and platforms for sharing, but they were not willing to be that open towards other competitors*." Therefore, she argued that IS relationships, as business partnerships, require building a relationship of trust that cannot take place through a digital platform alone: "*… it's not that you can just come and shop a flow of materials or… it's more a long-term relationship and it [IS relationship] needs to be prepared a lot for*" (O9).

Informational Barriers

One of the most cited barriers to IS is the insufficient information disclosure about the resources that are present in the industrial park, which hinders the identification of potential matches. As O6 explained: "*I don't know who has something that I can use. I don't know where it is. I don't know if it's enough, the volume, and if the volume of one [company] is not enough, how could we actually get the volume, collect more volume from others*." To address the lack of information and support the identification of synergies, many interviewees highlighted the need to actively collect information about all the assets and resource flows available in the industrial park through 'resource mapping'. However, this activity already requires substantial investments, making it reliant on external funding, such as governmental subsidy.

The quality of the information provided on a platform is also an important factor. In order to connect firms that seek and offer resources, an IS platform is reliant on the data that is published by its users. O5 pointed out that a platform could only work when firms publish trustworthy data about what they have to offer or supply. When companies publish incorrect information

about the demand or supply of resources, the ability of the platform to provide valuable matches decreases. This is especially the case for the descriptions of resources offered, as it is difficult for firms in need of a resource to determine the quality of what is made available through the platform.

Technical Barriers

Asset sharing and waste reuse opportunities outside of a single company do not seem to be considered worthwhile by most interviewees. As some of them explained, many companies do not participate in IS because it is simply not part of their own business: firms are specialised in their production activities to serve the market demand instead of optimising resource usage by cross-collaborations with other industries. As such, the (technical) competences required to identify opportunities for IS are not regarded to be in line with their core business activities.

Additionally, some interviewees argued that the lack of competence could hinder the success of an IS platform in the industrial park where they are operating. O7 suggested that the current generation of firm managers may not be familiar enough with new digital technologies, whereas $O2_2$ questioned whether sharing information about excess resources to address the lack of transparency would be enough to support IS matchings: "*And even if they put it [information about excess resources] out there [on a platform], do the companies have sufficient competence and knowledge of how to use all the different material types? I doubt it to some extent. Maybe there should be someone who is active with seeing how we can use these kinds of materials in different other areas*." Sharing assets and exchanging by-products require specific competences in which firms are not specialised, thus few interviewees suggested that a third party, such as a consulting company, is needed to facilitate IS.

Economic Barriers

Many of the challenges to IS described by the interviewees are economic in nature. Although IS has the potential to yield profitable exchanges for industrial firms, they argued that for many transactions the business case is too small or uncertain. Therefore, companies are reluctant to engage in IS projects that require "*too much investment on uncertain terms*" ($O2_1$) to initially assess IS opportunities. In addition, after the identification of potential symbiotic exchanges, firms often have to make large investments to enable the actual operationalisation of the resource exchanges, for example, in logistics or changes to the production system. Because of these extra costs, the potential economic returns cannot be expected in the short term. Therefore,

a few interviewees discussed the need for external financing. O8 argued that the government could play a more active role by financially supporting firms with IS projects. However, this may lead to a dependency of IS platforms on governmental funding to work, thereby making the long-run viability of IS uncertain.

Furthermore, the risk of ending up with a less profitable production process by using by-products can discourage firms to consider IS. Companies are not willing to risk the stability of their existing industrial operations, as inputs from IS may be of variable quality or availability. When an alternative resource supplier is considered, the supply must be steady enough to ensure no economic loss. Sound feasibility studies could support the firms' decision to invest in IS projects.

Companies' Interest in a Platform-enabled IS

Most interviewees recognised the potential of digital platforms to facilitate IS. In the words of O1, a digital platform can help "*to create an even better marketplace for the industries, bringing up competence, bringing up competitive edge, being even more efficient*." Yet, a few interviewees questioned the need for an IS platform in their industrial park. Some argued that participation in an IS platform would be more interesting and feasible for large firms than for small and medium-sized enterprises (SMEs). Making such a platform work requires firms to publish what they have in excess by providing reliable and up-to-date data about their by-products and excess capacity. Most interviewees pointed out that the larger firms in their area would possess good internal information systems that keep track of the occupancy of the production capacity and the streams of by-products. In contrast, small firms do not have this data available and will have difficulties with finding time and resources to publish the data. According to $O2_2$ and O6, small firms also have less to trade on the platform and would thus not see the benefit of investing in the documentation of their resources and assets.

Most interviewees agreed that IS platforms should be easy to access and use, compatible with the systems already in use, and show upfront the financial benefit of joining. In addition, $O4_2$ argued that the platform should confront the firms with the environmental impact of their business-as-usual compared to engaging in IS as this could provide an additional incentive for firms that are committed to sustainability. Being in the planning phase of a platform for their industrial area, $O2_1$ and $O2_2$ also recognised the importance of promotion to make firms join their platform. In their project, they plan to on-board an initial group of firms that are already practising IS to

advertise the profitable collaborations between these firms as an example for others. Next to showcasing the success stories through different channels like social media, local newspapers and a dedicated website, $O2_1$ planned to visualise the resource flows of existing IS collaborations in the industrial park.

IS Platform Design

To investigate how digital platforms could be designed to enable IS, we turn to such platforms that are operational in the Netherlands, and compare their design with some of the results from the Norwegian respondents.

Platform Features

Parksharing (D1) is a private B2B online sharing marketplace developed by Floow2 and launched in 2018 to support the exchange of by-products and assets (*e.g.* unused materials, services and facilities) among firms within and across Dutch industrial parks. The platform is delivered in collaboration with business park management organisation Solaris Parkmanagement (P3) and Symbiosis4Growth, which facilitates work sessions to link companies and help them find collaboration opportunities. Municipalities or industrial park management organisations can approach Floow2 to develop a customised platform, often with financial support from the government. Companies are offered to use the platform without costs for a limited period of time (*e.g.* one year) to try it out and encourage usage. This strategy is common in setting up digital platforms to solve the chicken-and-egg problem, that is, to ensure sufficient supply and demand (Rochet, Tirole, 2003). After this trial period, firms have to pay a fixed access fee per month to be able to make their demand and supply visible on the platform. Already more than 1500 firms have created an account on the platform.

Conversely, InduSym (D2) operates an open platform for companies to demand, supply and share residual flows and assets. TU Eindhoven graduate Immanuel Geesing, in collaboration with Stichting Bedrijventerreinen Helmond (SBH), a park management organisation, and Twinvision Software, an IT company, developed the platform that was launched in 2017. The platform was originally created as a tool that SBH could use to facilitate IS matching among firms located in the industrial park, but is now turned into an open platform for all companies that want to be involved. The platform is currently owned by a foundation with a daily board consisting of Geesing and two representatives from SBH and Twinvision Software. Two freelance consultants are working for the foundation to facilitate the IS resulting from

the platform. The primary goal of Stichting InduSym is to support SMEs in the transition to a circular economy. Firms that are interested in participating in the platform can create an account for free and log in to offer and request residual material flows and assets. An algorithm matches the firms in the network, who can then negotiate and settle the transaction among themselves. However, to collect data for the platform, the foundation developed a 'materials-scan': a paid service that is offered to end-user firms or park management organisations to identify opportunities for IS. Resources that cannot be matched within the direct network of the consultants are placed on the platform. Approximately 250 firms have signed up for the platform.

Data Security

According to D2, the only real requirement that users set to an IS platform is that data needs to be treated securely and with integrity. However, there is not much data shared about the firms through his platform, because the accounts are initially set to publish demand and supply anonymously and users can optionally add information about their company. In addition, the firms do the communication and transaction between themselves after they have been matched via the platform, so no financial data is collected by the platform. Similarly, users of D1's platform can decide what information are publicly available online. Even though the two platforms offer the option to stay anonymous, both D2 and P3 argued that it is beneficial if firms reveal their personal details when publishing their demand and supply because then both parties already know what kind of organisation they will come in contact with.

Compatibility with existing firm activities

Just as some Norwegian interviewees, D1 argued that it should be easy to start using the platform so that it can blend in the company's daily business and deliver the value that it proposes. She explained that firms often think they need to radically adapt their production processes to become circular, by for example redesigning their products. On the contrary, an IS platform provides firms with the opportunity to become more circular while performing their usual activities.

Involvement of Competence

Another important aspect for a platform is the presence of competences to realise IS. P3 pointed out that there is a difference in complexity between

asset sharing and resource exchanges. The former is relatively easy, since hiring out assets is rather straightforward and the correct product usage can be learnt with instructions. Conversely, the realisation of the latter is more difficult and requires additional competences. According to D2, some matches are easily identified, the 'low hanging fruits', but many others need technical knowledge or innovative and unexplored technologies to be discovered and implemented. Firms generally lack the required skills and experience; however, these matches could become viable when competences are provided by external experts. D1 offers this service by means of a partnership with Symbiosis4Growth, an organisation who helps firms identify the business case of exchanges that would otherwise be too complex to make between the firms themselves. D2 has connected freelance consultancy services to the platform that can be used when questions about the matches made through the platform arise.

D2 also indicated that there is less specific competence required to offer materials on the platform (supply side) than to be able to use the offered materials (demand side). It is easier to identify what materials can be exchanged since it is often waste that would otherwise be disposed of. However, to identify how these resources can be used as an input requires specialist knowledge. D2 explained: "*What we see in the platform is that there is more supply of by-products that there are takers of by-products. So, for a firm to really dare to say: 'I know how to use this product to produce something' surely requires technical or substantive knowledge about the material*." This means that the demand-side of the platform is underrepresented due to a lack of competence, thereby limiting the indirect positive network externalities for the supply side. The imbalance limits the ability of the platform to provide the supply side with valuable matches with the demand side.

Platform Governance

Another design requirement identified from the interviews is the control of the behaviour of platform users. P3 explained that one of the firms in the industrial park had used the platform to sell its end-products instead of by-products. This is not in line with the value proposition of the platform, which wants to stay exclusive for firms that search for IS opportunities to keep its credibility. The platform prevents this adverse behaviour by warnings and, possibly, by banning users that exhibit adverse behaviour.

Similarly, the barrier of trustworthiness of information also indicates that platform users need to behave in a certain way to maintain the value of the platform. Namely, when platform users publish incorrect information about

their request or offer, the platform's ability to make the right match decreases. The platform, therefore, has to enforce the desired behaviour by setting usage rules and subsequently punish users when they violate them.

Encouraging User Participation

Before a critical mass of users is reached, the platform is not able to deliver the value that is intended to offer. P3 illustrated this for the industrial parks that she manages: "*They [participating firms] have to publish something, then they have to be matched, but that match is still not right every time, because sometimes the demand does not connect well with the supply. And when the first experiences are not entirely satisfactory, the people often think 'well, never mind, I'll just ask my neighbours if they can help outside the platform*'." This answer confirms the concern of some of the Norwegian interviewees that firms may not trust the platform to deliver direct results. Therefore, it is important that the first experience is successful to convince the firms that the value of the platform is worth the effort to participate.

D1 dealt with this problem in two ways. First, they used their partnership with a park management organisation (P3) to involve many member firms at the same time and create a critical mass of users. Still, the on-boarding of firms went "*super slow*", which made them see the need to partner up with another organisation, Symbiosis4Growth, to further encourage companies to engage in IS. Together with this organisation, the platform organises meetings, or 'work sessions', with firm representatives to actively identify opportunities for IS. The goal of these sessions is to use the knowledge from the firm representatives about their resources and the competence of Symbiosis4Growth to identify as many matches as possible. The resources that are not matched during the session are published on the platform, thereby increasing the amount of content available online.

The provision of work sessions is one way to support firms to become affiliated with the IS platform. To reach a critical mass of users, the platform needs to provide such stimuli, which can be done in several other ways. A strategy that both D1 and D2 use is collecting the offerings and requests for resources and assets by themselves. In this way, the platform unburdens the firms from the effort of publishing the demand and supply on the platform. D1 does this through the partnership with the park management organisation of P3, who visits the firms one by one to inform them about the park management services, including the IS platform, and asks if they have excess resources to supply that can be published on the platform. Besides, the platform provides an online 'scan', which is a free-of-cost questionnaire that can

be filled out relatively quickly by the firms themselves to calculate in advance the potential profits of exchanging underutilised resources. At the end of the questionnaire, the firms are invited to publish their excess resources on the platform. D2 takes a slightly different approach by selling interested firms a service (materials-scan), whereby a specialised IS consultant assesses the opportunities of IS for the firm. According to D2, the firms are not yet committed enough to IS to take the effort of making an inventory and publish it on the platform: "*So, we got around that a little, because we provide that scan, we fill them out for them. […] So, we drop by ourselves and make the inventory of the data ourselves*." The firms are provided with valuable matches from the direct network of the consultant and the unmatched resources are published on the platform, to be matched with other participants in the future.

Next to filling up the platform themselves, Dutch platform developers/providers encourage user participation by means of subsidies. The use of the platform is offered for free for one year by D1, although she stressed: "*We have always said from the beginning that we are willing to facilitate towards the entrepreneurs for free, but not forever. So, at some point, there has to be a financial incentive for those firms to use it*." The usage of D2's platform is instead completely free of charge since its revenue model is not dependent on membership or use of the platform.

Platform Promotion

As explained by Norwegian industrial park organisations, it is not among the standard business activities of firms to be engaged in IS or use a platform to offer and request resources or assets. D2 commented about this: "*The main barrier is in fact to reach the entrepreneurs and get them enthusiastic. […] you need to have the right channels*." For this reason, D1 collaborates with P3 to be able to promote the Parksharing platform in the industrial parks that are managed by P3. First, they introduced the project at general meetings, then they started a marketing campaign via social and local news media. Also, through the periodical newsletter of P3, firms have been instructed at the beginning on how to use the platform and later reminded to start using it. D1 stressed the importance of the collaboration with P3, as the park management organisation already has the connection with the entrepreneurs and is, therefore, able to use existing channels to promote the platform. As D1 explained, by using the collaboration with an organisation like P3's that unites many firms, you have "*one front door*" that enables you to easily approach a large number of firms and reach momentum, or critical mass. However, D1 and P3 both remarked that it is still difficult to bring the platform under the attention of

firm managers and it is important to repeat the communication to constantly remind the firms to use it.

Similar to $O2_1$ and $O2_2$, who want to use the success stories of existing IS collaborations in the industrial park to showcase the potential of IS and convince others to join their future platform, D1 adopted this approach in collaboration with P3. She explained that in each industrial park they asked several companies if they had items they could share, to use them as examples for the platform. The firms that were willing to participate are called 'ambassadors' of their industrial park and their stories were featured in promotional videos.

Change in Mentality

The adoption of an IS platform requires firms to be committed to sustainability, as stressed by D1: "*They actually never have to think about other things than executing their daily production processes. Therefore, they really have to do it [joining an IS platform], because they want to do good for the environment and many firms just don't have that.*" Companies still prefer to buy new resources and assets from the suppliers they already know because it is easy, fast and reliable; whereas IS appears more time consuming and requires more effort and insecurity compared to the conventional way of production and procurement. "*What we noticed with entrepreneurs, is that they are really occupied with doing business. They really want to help their neighbours, but they often say already: 'Oh, my secretary will do that, or someone else', because since they are so busy with their daily activities, such things are quickly forgotten. Besides, it is still a purchasing economy; it has become too easy to just buy new things.*" (P3)

$O4_2$ suggested that platforms should confront firms with the environmental consequences of their current business activities to provide them with an incentive to engage in IS. This was one of the reasons for D1 to develop the online scan that firms can use to calculate what participation to the platform could yield in economic and environmental terms. By providing this easy and accessible tool the change in mentality can be encouraged, which increases the chance that firms will use the platform. According to D2, the required change in mentality is not expected in the near future, but the societal transition is already set into motion. Also, D1 pointed out that it is going to require perseverance from her organisation: "*We just know that there are many excess by-products and underutilised assets; at any firm, that's just a fact. But a lot of entrepreneurs are not yet thinking about it [exchanging and sharing resources], because they're doing things the same way for 50 years and it's going just fine like this.*" However, D2 argued that IS is one of the rare

kinds of sustainable practices that yield economic returns that, whether in the short or long term, provide a business case as motivation. Moreover, the price of secondary resources will eventually rise, resulting in an even stronger incentive for firms to engage in IS, since exchanges through the platform will suddenly become profitable. Here, there is also an important role to be played by the government to encourage and incentivise the choice for IS.

Supportive Governmental Policies

The government has a large impact on the choices that firms make by setting regulations and granting subsidies. The role of the government is thus often pivotal for setting circular practices in motion. One of the barriers to IS at Norwegian industrial parks mentioned by O8 is the reliance on external funding. The two cases of D1 and D2 confirm the issue of financial dependency on the government, as both platforms are financed with subsidies. Some local governments that have the circular economy on their agenda made funding available to financially support the organisations of D1 and D2, which enabled the establishment of their platforms. D1 emphasised that the platform is intended to become independent from subsidies: "*And in the end, it has to become a sustainable platform. So, what you often see, is a platform entering the market without a revenue model. Then, in fact, you do not have a future, because you cannot sustain from subsidies forever. That is impossible and that was also a requirement from the government that the platform would eventually become self-sustaining.*"

Discussion

The interviews with Norwegian industrial organisations provided a detailed picture of perceived barriers to IS and how digital platforms can help overcome them. These barriers are largely consistent with those identified almost a decade ago by Golev *et al.* (2014). While pressures on industry to contribute to sustainability and transition to a circular economy are mounting, most firms still appear to prioritise economic interests over environmental impact, or limit the scope of their action to 'low hanging fruits' that do not require substantial changes in established procurement and production processes. Norwegian interviewees also confirmed a tendency among firms to work in silos, with limited knowledge about – let alone collaborations or exchange of information with – other companies located in the same industrial park. The technical feasibility of IS was described as another key barrier to the exchange of by-products: companies lack the expertise

necessary to identify and take advantage of synergistic transactions, since these capabilities are traditionally not part of their core business activities. To address this problem, the two Dutch platforms we interviewed provide easy-to-use tools and consultancy services to their users. Last, Norwegian industrial park organisations questioned the economic viability of IS exchanges. The business case for IS remains, according to them, too little and highly uncertain. Environmental legislation and difficulties to obtain approval for waste reuse projects from the regulatory authorities, on the contrary, were not considered an obstacle by the Norwegian interviewees. This could possibly be explained by recent developments in national and EU (waste) policy that aim to contribute to the realisation of a circular economy, *e.g.* the framework of the European Green Deal (European Commission, 2022). An IS enabler described in the literature that was not mentioned by our interviewees is community awareness of the environmental and economic impacts that industries generate. This suggests that limited communication (or engagement) currently exists between industrial organisations operating in Norwegian industrial parks and local communities. The latter seem to be hardly considered a relevant stakeholder group by our informants, despite IS synergies can induce territorial development (*e.g.* by fostering the emergence of new markets and innovative technologies) (Kasmi, 2020) and local communities can play an important role to ensure the legitimate status of IS synergies (Golev *et al.*, 2014; Henriques *et al.*, 2021).

When looking at the specific challenges to the successful implementation of matchmaking IS platforms, we found that the exchange of by-products is more difficult to realise than the sharing of underutilised assets. The difference in complexity between asset sharing and by-product exchange can be explained by the different degree of standardisation of traded goods. A specific asset (*e.g.* a car, forklift or wooden pallet) offered via a platform can be regarded as relatively identical, regardless of which firm supplies it. For the exchange of by-products, by contrast, there are many more requirements related to the quality and quantity of the resource made available, which make it necessary to collect more and specific information to find the right match. This may explain why some digital platforms are set to facilitate the process of synergies identification and exchange for only one type of waste/resource stream (Bonnet *et al.*, 2016), which is considered one of the limitations of existing IS platforms (Kosmol, Leyh, 2020). Moreover, our Dutch interviewees explained that less standardised resources require more (in-house or external) expertise to become a valuable and reliable substitute for virgin resources in the production processes of firms. For this reason, it is somewhat easier for platform operators to increase the available offer of excess resources (supply side) than to find companies interested in buying

them (demand side). A final challenge relates to short-term *versus* long-term agreements. The exchange of by-products most often involves a long-term agreement to ensure a reliable stream of inputs and outputs for both platform users. Digital matchmaking platforms, however, benefits from supporting many small transactions (in a homogenous market) as these create a thicker market and larger, positive indirect network effects. Furthermore, a high volume of transactions increases the amount of feedback and ratings that firms could publish on each other, thereby solving trust related issues by reducing the number of low-quality sellers or buyers. Overall, matchmaking platforms can help overcome some of the existing barriers to IS (*e.g.* informational and technical barriers), but appear better suited to lower transaction costs in homogenous and dense markets (*e.g.* Airbnb) than in the highly specialised and heterogeneous markets that are typical of geographically-bounded IS networks.

Conclusions

Industrial Symbiosis (IS) describes the mutually profitable transactions between traditionally separate industries based on the sharing of underutilised assets and the exchange of waste/by-products. A promising role in supporting IS could be fulfilled by digital platforms, which can act as online marketplaces and facilitate the interaction between two distinct groups of users, here, resource suppliers and buyers. Despite the benefits, the uptake of digital platforms for IS has remained low thus far, and limited empirical research exists on how running IS platforms are designed to address the barriers that hamper the realisation of IS networks. Our results show that IS platform developers and providers try to solve cooperation and technical barriers by organising workshop sessions for firms to meet and explore synergetic opportunities, assisting with the collection of relevant data, and providing purpose-built tools and expert knowledge to support the identification and implementation of IS exchanges. To overcome possible data confidentiality concerns, the IS platforms operational in the Netherlands are also designed in such a way as to reduce the need for sharing sensitive company's information. Moreover, environmental and economic gains are quantified and visualised to reassure firms of the financial viability of IS transactions and motivate firms committed to sustainability. Altogether, platform design and governance mechanisms appear thus crucial to facilitate circular economy projects at the territorial level and foster the wider uptake of IS.

Nevertheless, our study also uncovered challenges especially relevant for matchmaking IS platforms, which are hardly addressed in extant IS

literature. The main one is related to solving the 'chicken-and-egg' problem between supply and demand as to reach a critical mass of users on both sides of the platform. To recruit as many users as possible, platforms can either be open to all companies interested in IS exchanges, or collaborate with industrial park organisations. Both platforms under investigation facilitate exchanges of underutilised assets as well as waste/by-products: the former ensures a high volume of transactions and, possibly, a thick market; whereas the latter entails one-off transactions that can unleash the full economic and environmental potential of IS. Yet, both platforms currently still subsidise user participation and are, thus, dependent on (financial) governmental support to work.

Although the findings are difficult to generalise due to the low number of interviews conducted and their context specificity, our results suggest that existing platforms only partly address the (still many) barriers that prevent the realisation of IS synergies and the need for a more prominent role to be played by governments to support the development of IS platforms as a way to promote digital innovation and a transition to a circular economy. Yet, one of the major hurdles to IS remains the firms' lack of commitment to sustainability and a low price of virgin resources. The importance of sustainable sourcing and responsible processing of industrial waste/by-products is increasingly recognised at a policy level, *e.g.* in the EU's circular economy action plan (European Commission, 2022). Albeit slowly, a change may have been set in motion for a platform-enabled IS to become a widespread reality in the near future.

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Appendix

Interview guide for Norwegian industrial park organisations (summary)

	Topics discussed
Interviewee's profile	Position/role in the organisation, background and experience
Organisation's characteristics	Year of establishment, mission and products/services offered, organisational structure and activities
Industrial park's characteristics	Number and type of organisations located in the industrial park, geographical scale, existing relationships between firms in the park, importance of environmental aspects and access to expert knowledge
Existing IS exchanges	Resource exchanges in the industrial park (type, coordination, tools used, business models) and barriers to IS
Digital platforms for IS	Opportunities and challenges of using a digital platform for IS, design features and coordination of digital IS platforms, interest in the platform and barriers to adoption/use

Interview guide for IS platform providers (summary)

	Topics discussed
Interviewee's profile	Position/role in the organisation, background and experience
Organisation's characteristics	Year of establishment, mission and products/services offered, organisational structure and activities
IS platform's characteristics	Development of the platform, functionalities, design requirements/features and business model, actors involved (*e.g.* owner(s), investors, industrial park organisations, IS consultants)
IS platform use	Number of (active) users, characteristics of early adopters, IS exchanges/matches facilitated by the platforms, barriers to adoption/use
Lessons learnt	Success factors for IS platforms, challenges experienced and possible improvements, growth potential, role of digital platforms to enable IS exchanges/circular economy