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Industrial Symbiosis - Recommendations on a business framework conducive for successful Industrial Symbiosis at the Kwinana industrial area

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Abstract. With an extensive presence in the world of Industrial Symbiosis literature, the Kwinana industrial area in Perth, Western Australia is a powerhouse of integrated heavy industrial activity. From when its first entrant arrived in 1955, development has been strong, and now it presents a complex industrial cluster with a wide range of industrial enterprises present, ranging from several major industrial multi-product manufacturers to those filling niche markets. Formal reporting of its economic contribution has occurred periodically over 40 yr, with one of the features of this being a series of four earlier iterations, and in this paper, the fifth, of a schematic diagram that identifies the enterprises engaged in symbiotic relationships and the nature of the associated materials exchanged. While the earlier reports concentrated solely on the traditional materials exchanges, the present study (data collected in 2021) went beyond these to gather additional data on what the authors are proposing as additional dimensions of the traditional Industrial Symbiosis framework. Aspects of Kwinana's skilled workforce, its support industry base, and its overlying governance framework were studied to provide insights into what role they play in explaining why some industrial clusters appear to provide a supportive business environment, and why other clusters struggle to gain momentum. The new study identified that the novel posited dimensions of Industrial Symbiosis are interlinked at the precinct level, and that at the macro (societal) level, they combine to contribute to the effectiveness of the Circular Economy.

Keywords: Industrial symbiosis / KIC4 / four dimensions of Industrial Symbiosis / Circular Economy / skilled workforce / governance

1 Introduction

Industrial precincts exist throughout the world and each has its own particular output mix or focus. This can range from highly specialised clusters of similar enterprises engaged in fierce competition for market share and operating in isolation whilst essentially being neighbours, to those that are incredibly diverse and where there exists problems and opportunities that can be shared. Enterprise diversity can be used as a strength to encourage commonly held issues (and opportunities) with the potential for pursuing through their collective actions. If therefore, there can be some way in which industrial precincts are or can be made more conducive to the improved competitiveness of a cluster of resident enterprises in a structured way, is this not something worth pursuing?

The purpose of this paper is to bring forward and test a theoretical framework that redefines and expands the long-held view that industrial symbiosis (IS) is a single-dimensional construct, relating exclusively to the exchange of process by-products to reduce waste.

The objective of this paper is to test for the presence of other dimensions of IS and to attempt to consolidate the proposed four-dimensional IS framework (KIC4). This has been previously conceptualised as an applied process by which any given industrial precinct may be evaluated for its effectiveness against four posited dimensions. To support this, it will be demonstrated that the four dimensions can be used as a potential framework for the broader evaluation an industrial precinct for its symbiotic credentials.

A formal evaluative approach to build an understanding of the characteristics of industrial precincts was completed and the data utilised within this paper. This

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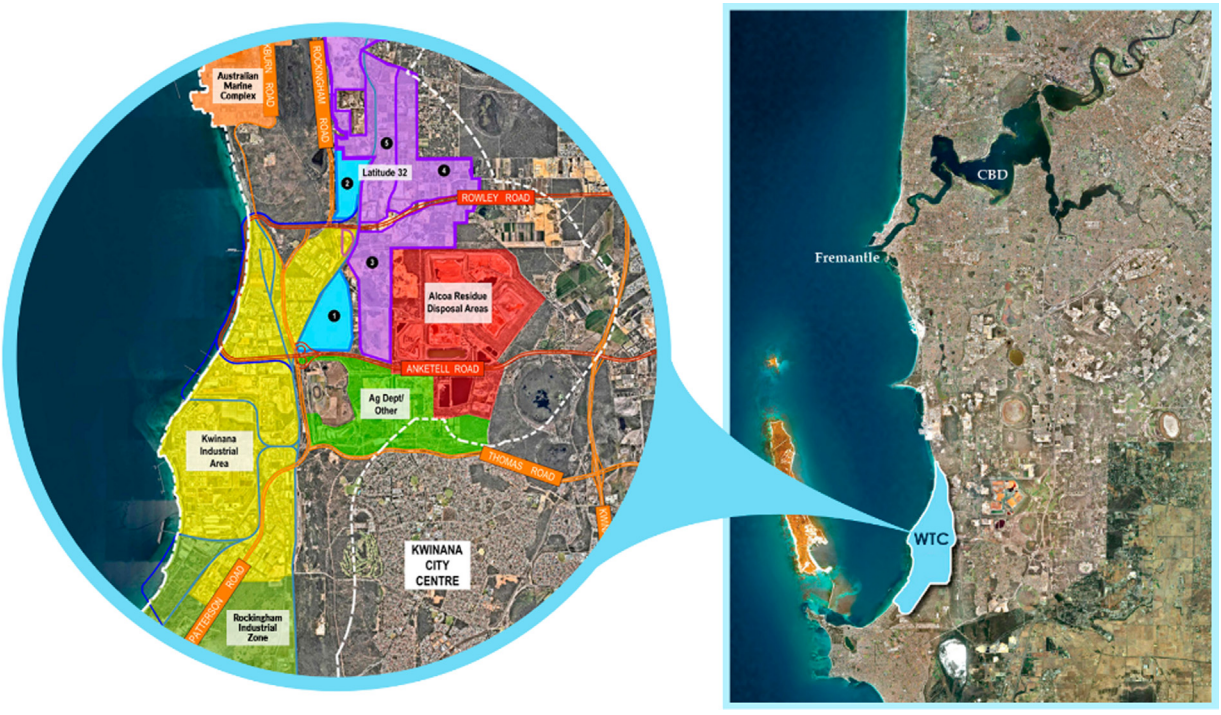

Fig. 1. The western trade coast and its industrial hubs located within the Perth Metropolitan Area of Western Australia [4,5].

process was facilitated by focusing on a well-researched and major industrial precinct located in Perth, Western Australia (WA), the Kwinana Industrial Area (KIA).

About Kwinana

Located within the Perth metropolitan area in WA (Fig. 1) is a major industrial zone referred to as the Western Trade Coast (WTC) [1]. Located on the coastline within the WTC is the strategic industrial area referred to as the KIA, which is where the heavy industries in Perth have been clustered for almost 70 yr [2–4].

The range of product categories manufactured from within the KIA is broad, and its freight networks are deeply connected into the mining and agricultural regions internally within WA, and externally to other parts of Australia and beyond into the industrial product markets of the world. Established as WA's first strategic industrial area in 1950, the first industrial facility to be commissioned there was the BP oil refinery in 1955. During subsequent years, major companies were attracted to the KIA and by the late 1960 s, there were several additional major facilities commissioned, including an alumina refinery, cement and industrial lime production facilities, a nickel refinery, a pig iron blast furnace and rolled steel production plant, fertilizer production and other chemical production plants.

Sinclair Knight Merz (SKM) reported that from the mid-1960 s, new major industrial enterprises were being attracted to co-locate near suppliers of the input materials required for their production processes, and service industries being attracted to locate nearby to their customers [6]. Major freight infrastructure (road, rail, and bulk goods port) was installed by the government of the day, and the attractiveness of the precinct as a place to establish an industrial facility continued to grow. The industrial ecology of Kwinana had entered a strong growth phase that would last for decades.

In a testimony to that strength, and to the interconnectedness of the enterprises located in the KIA, a major resurgence in construction and pre-construction activity is currently underway. New industrial projects in planning or under construction include Australia's only two waste-to-energy plants, two lithium hydroxide refineries, two nickel sulphate precursor battery materials refineries, two high purity alumina and two graphite facilities, a cobalt and a manganese oxide refinery, and two (one blue and one green) hydrogen/ammonia production plants. Several existing enterprises are expanding their production or storage infrastructure to support the input materials requirements of other enterprises located within the precinct. The WA State government is deeply engaged in the planning for a new container and break-bulk port facility in Kwinana to augment the existing bulk materials jetties, and with that will come upgraded rail and road freight infrastructure to facilitate the additional trade [7,8].

Motivation of the research

This research is motivated from the perspective that for industrial precincts to have characteristics that are conducive to the commercial longevity of the resident enterprises, positive synergistic relationships across a number of dimensions need to be evident [4]. This paper uses the KIA to illustrate how synergistically interconnected enterprises within a defined industrial precinct can continue to operate commercially whilst still responding to

broader Circular Economy (CE) goals. Utilising research into how the materials exchanges in Kwinana have evolved since previously measured (SKM 2014), and by presenting data about the impact of three other dimensions of IS, we identify the impacts on the nature of the Kwinana precinct [6]. This objective approach can be applied to any industrial precinct to aid in the achievement of commercial sustainability and of course, societal CE goals.

Underpinning all of this is the unseen but very extensive network of product, by-product and utility exchanges associated with the KIA [3,7,9]. These industrial symbiosis (IS) exchanges were first documented in 1990 [10], and over the years were reviewed and re-presented on three further occasions, in 2002, 2007, and 2014 [6,11,12]. What is clear from the data gathered in this study (2021) is that the number of participating industries and indeed the number of materials exchanged between them grew substantially over the years. Extensive guided tours of the WTC are regularly provided for parties with an interest in understanding more about the industrial area. Almost invariably the direct feedback from participants (including scientists, academics, industrial proponents, and public servants), has been that people simply had no idea how extensive, diverse, constrained, and integrated the KIA was. Representatives from potential new entrants are drawn to the KIA's IS story, which often features as a prominent factor in their locational choice when they establish in Kwinana. The relationship between a sender of a by-product and a receiver, for example, is necessary to create a successful exchange. We posit that relationships also exist between the cluster's primary enterprises and their collective workforce, and between the primary enterprises and the lower tier ones that provide the goods and services that are needed for business continuity. Further, there is a relationship between the primaries and the government departments that define and deliver the policy environments and state infrastructure within which the cluster operates.

The implications for practitioners, researchers and policy makers, therefore, is that there can be a structured framework which supports the creation of knowledge about what needs to be done to assist industrial precinct managers to provide supportive environments within which the domiciled enterprises are enabled to operate in a less-constrained, or even in an environment that is more conducive to business operations.

2 Methodology

This section has three parts, with the first being a literature review to seek and support the basis for an expansion of the definition of IS into the posited four dimensions. This part looks at the traditional framework for IS and then at the contemporary interpretation or evolution of this. The second part draws the contemporary research into the KIC4 model. The third describes the research methodology employed.

2.1 Literature search

Following a comprehensive review of the literature it was observed that the definition of IS had been expanding beyond the traditional definition which was confined to the re-use of waste and by-product materials. Lombardi and Laybourne provide a useful insight to support this [13]. They posit that IS encompasses a diverse range of enterprises in an eco-innovation environment, where knowledge is shared to deliver profitable outcomes, reduced waste and value adding, with improved business processes as a result.

2.1.1 The traditional framework

Oughton et al. [5] in acknowledging the work of Lombardi, and numerous other scholars, posited that IS was not limited to the exchange of waste and by-product materials, indeed, that this traditional view of IS was but one of four dimensions of IS. From this point we refer to the exchange of materials within an industrial precinct as D1. To be consistent, the other three dimensions are similarly referred; presence of a skilled workforce (D2), the presence of the support industries required by the industry majors (D3), and the governance environment (D4).

Some recent studies have sought to expand the thinking around the broader relationships observed to be operating within and around industrial clusters. Taddeo et al. (2017) posits a model that connects the urban, rural, industry and waste/energy interactions that exist between these "dimensions" of eco-industrial parks [14]. Others have attempted to identify success and limiting factors for existing industrial parks [15]. Sakr (2011) for example identified six success or limiting factors that can affect the development of an eco-industrial park, and went on to identify the lead agency roles for each factor [16].

This expansion of the traditional definition of IS is being characterised as a new model to describe it and is referred to as the KIC4 framework for IS [5]. This paper researches the conceptual expansion in the traditional material exchanges and the extent to which the remaining three dimensions are present in the minds of the boards and management of the resident enterprises. The exploration of these dimensions in this paper lays the groundwork for further research on the subject.

The research has been positioned within the wider research field of IS, and this was presented by Oughton et al. (2022) in their comprehensive (systematic) review of the literature [5].

During the decades leading to the turn of the century, much scholarly research in the field of social and technical inter-relationships between people and technology, and how these can be optimised for improved production and organisational performance occurred [16]. Since then, research has identified that the field of IS has evolved through a set of frameworks, moving through post-war systems theory, through to what we now see as frameworks

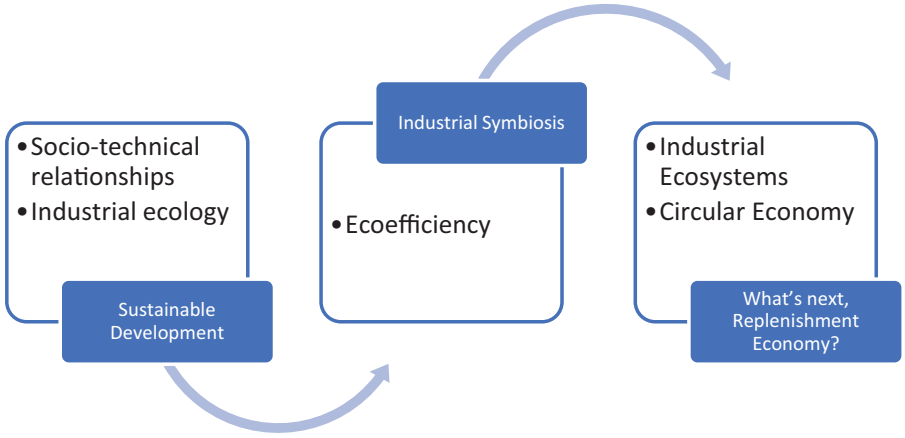

Fig. 2. Progression of the frameworks [5].

that may be described as enterprise-centric. A CE is now considered an expression of a new and far broader theoretical framework [4,9].

In our comprehensive literature review, the theoretical encapsulation of IS was recast, and it presented the novel idea that the traditional definitions of IS (re-use of waste and by-products within an industrial cluster) fall into but one dimension (of four) of what we view as being multi-dimensional industrial relationships [4]. Lombardi and Laybourn (2012) introduced aspects of enterprise ecoinnovation and culture change, seeing the emerging thought as leading to other less definable aspects of IS, and effectively broadening the traditional world view of IS to encapsulate all materials exchanged within an industrial precinct, including those manufactured for redistribution within it [13]. Branson (2016) in his research paper focusing on the well-regarded Danish industrial precinct, Kalundborg, sought to further re-cast what constitutes IS, where the goal is to achieve eco-industrial sustainability. While positing further research into this, it was concluded that sustainability is determined by whatever is the practical outcome following the application of theory [17,18].

2.1.2 The contemporary framework

Our research effectively presented the idea that the traditional view of IS and its orientation towards ecological sustainability could be expanded into areas that up to that point in time had not been associated with traditional IS. In providing an overview of the historical evolution, Oughton et al. (2022) observed that IS over the decades had evolved from its early form as sustainable development, evolving under various emerging frameworks including eco-efficiency, then IS, until today where the current CE framework is now evolving towards a replenishment model (Fig. 2) [5]. Other models have emerged where the exchange of materials is re-defined. Indeed Kurup's (2007) 'Six Capitals' model brought in the broader economic, social and environmental impacts of IS, thus continuing the broadening out of single dimensional view of IS [19]. This work has brought about a greater understanding of the benefits accruing to the enterprises located within an industrial precinct where they have the opportunity to participate in the exchange of products manufactured locally for the use (raw materials), and where waste or by-product materials are available for reuse.

Modern literature appears to be directing its attention toward the CE, with recent scholarly papers attempting to define these. Nikolaou et al. (2021) observe that there are varying views amongst scholars as to whether the term is separate from the more traditional term, sustainability [20]. In addition, they posit that as society moves towards increasing circularity, enterprises within the industrial setting are less likely to generate waste (IS), and that this falls within a higher societal framework responding to regional or national economic policies. Moreseltto (2019) described this as being an economic approach directed toward the efficient uses of resources [21]. Walker et al (2021) in their survey of European national and international companies, observed that CE was regarded as a tool to be used to strive toward the environmentally friendly use of resources, thus supporting the broadening of the traditional definition of IS [22].

2.1.3 Towards a new framework: the KIC4 model

Oughton et al. (2022) observed that an industrial cluster is impacted by a range of inapparent characteristics that help to define a particular location [5]. According to the authors, an industrial cluster that is attractive for new industrial enterprise to locate or to re-invest in their own ongoing development, is better than one that seems lack-lustre and failing to support the attraction of new enterprises or resident enterprises. Further, that the underlying reasons for this disparity of attractiveness appears obscure. They put forward four factors within a framework which was collectively referred to as the KIC4 Framework for Industrial Symbiosis. In their conclusion they posited that in addition to the traditional view of IS, there were at least three further symbiotic dimensional relationships, with each appearing to exist more predominantly within the more mature and successful complex industrial clusters.

Under the KIC4 framework, D1 was referred to as the product and by-product synergy dimension, it being the traditional space within which IS operates. The vast amount of research associated with this traditional

perspective cements in place the acceptance that where an enterprise is interacting with others within a given industrial cluster for the purpose of materials exchange (including by-products), it is a relationship based on mutual benefit derived through the exchange of supply and production-related materials.

D2 is posited to be related to the collective of skilled workers associated with a given industrial precinct. This body of skilled workers is available to a new-entrant enterprise for both the construction and subsequent operation of the facility. New entrants are able to recruit from within the local pool of skilled workers who are employed within the precinct. The maintenance of the human and social capital of the skilled and experienced employee resource delivers economic benefit to the collective of enterprises [19], and to ensure sustained growth through the adequate provision of these skilled workers, it is essential to retain the local skilled and experienced workforce [23].

In a manner not dissimilar to D2, D3 refers to those businesses that are geographically co-located with the industrial primaries for the purpose of servicing their ongoing needs. This support industry sector has typically evolved alongside the major enterprises, their customers and clients. Due to their geographic proximity, they are able to collectively provide cost-competitive services and contribute to the overall competitive potential of the entire industrial precinct [24]. It was posited that the support enterprises operating collectively as a cluster within an industrial precinct, exhibits a synergistic relationship with the heavy industrial enterprises [5].

Finally, Oughton et al. (2022) identified D4 as a dimension in which an industrial enterprise's international competitive ability can be positively or adversely impacted by the extent to which the public governance environment is facilitative toward industry in general. Governmental policy (national to local), common user infrastructure, and regulatory frameworks impact directly and indirectly upon any given industrial cluster. For example, the extent to which an enterprise can achieve zero waste in a CE context is dependent on the regulatory regime associated with waste management [5]. In her paper about the governance aspects of IS, Velenturf (2016) concluded that whilst facilitating (traditional) IS is a proven approach to limit carbon emissions and resource recovery, and in fostering innovation, further noted that governance, and its effects on IS, remain under-explored. [25]. Research into the development of land-use planning principles and planning guidelines for use by the public sector to aid in the development of industrial precincts, within which clusters form, illuminated the importance of the governance dimension in the context of delivering Australian industrial precincts that will support sustainable development [26].

Golev (2014), based on the study of a large eco-industrial park in Gladstone, Australia, identified that non-technical barriers such as difficult regulation, low confidence in government processes, poor cooperation between the enterprises located within the cluster, problematic economic barriers, and poor information sharing were preventing IS (D1) from developing toward its potential, thus hindering the maturation process [27]. The series of SKM (1990, 2002, 2007, 2014) reports which were focused specifically on the KIA up until 2014, to a lesser degree reflected Golev's observations on Gladstone. The SKM reports proposed strategies to diminish the barriers that were identified by the enterprise representatives that were interviewed during the development of the reports. For example, the SKM study reported that confidence in the industrial waste regulator's regulatory framework [28] for the treatment of industry's 'waste' outputs insofar as its ability to support waste reduction initiatives, reduced from a low 21% in 2007 to only 6% in 2014 [6]. At around the same time as the 2007 SKM report was published, Kurup had evaluated the enablers of industry under her Six Capitals Model and concluded that positive benefits to industry (and therefore to the State of WA), were achievable [6,19]. Harris (2007) identified constraints to a more CE-focused industrial environment in Kwinana which were attributable to industry regulation [29]. In focusing in on the definition of waste and waste derived material [30], these constraints appear to still be relevant in the KIA (and indeed in WA), and it is pleasing to observe that the Industry Regulator is taking positive steps to facilitate resource recovery as evidenced in its report entitled 'Waste not, want not' [30–33] and by initiating an amendment of the Waste Avoidance and Resource Recovery Act 2007 (and its Regulations) [31]. From this evidence it is clear that activity in the governance dimension (public sector) impacts industrial activity and the evidence supports the proposition that a synergistic relationship exists between collective public sector activity and the industrial enterprises within an industrial cluster. It seems reasonable then, to posit that the collective of governing policy, regulation, and

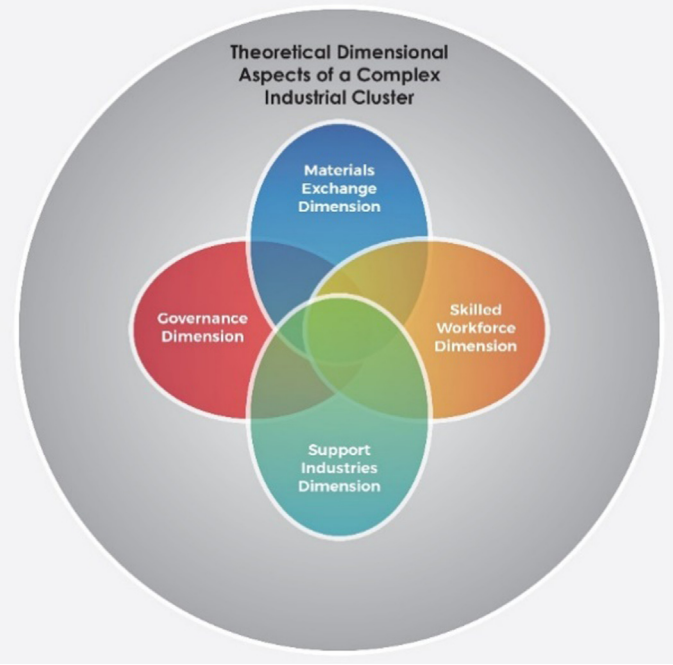

Fig. 3. Synergistic dimensional interactions [5].

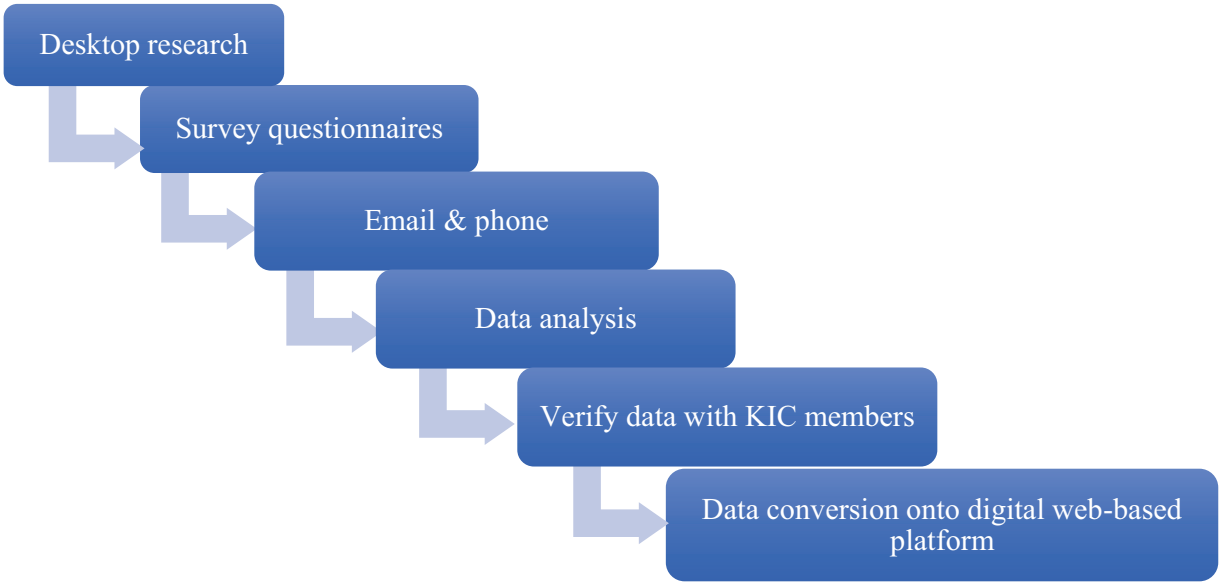

Fig. 4. Structure of the methods.

common-user infrastructure provision etc, has a synergistic relationship with the collective of enterprises operating within a given industrial precinct.

The four dimensions of IS presented each individually exhibited the characteristics of a synergistic relationship, that is to say there is a mutual benefit coming from the relationship between the two participating parties. Oughton et al. (2022) posited that for an industrial area to be present in a way that is conducive to the operational efficiency of its industrial inhabitants, the four dimensions need to be present and interacting in a synergistic manner. This point was illustrated (Fig. 3) in their paper, where the authors went further to propose that for an industrial cluster to be considered conducive to business activity, all four of the synergy dimensions need to be functionally present and interacting to some extent. For example, a skilled workforce cohort that is domiciled near to the industrial precinct that employs them clearly falls within the Skilled Workforce dimension. The precinct will therefore, to varying extents, form part of the character of the nearby community. An enterprise's social licence to operate derives from that nearby community, and social licence derives from the corporate boards of the precinct enterprises, where policy is made – this is within the Governance dimension and shows how dimensions can overlap.

To further demonstrate this point, we turn our attention to the Kwinana cluster, and to the commencement of the construction phase of the Covalent Lithium (lithium hydroxide) refinery project. The WA State government allocated an industrial site within the KIA to 'Covalent'. During the research for this paper, a senior project manager respondent, unprompted, referred to each of the KIC4 dimensions in his statement which is quoted here and with the addition of author underlining and dimensional References.

"The Kwinana location was selected for several reasons, including the co-location of similar industrial operations which can more efficiently share each other's infrastructure and buffer zone (D4). The Kwinana Industrial Area is close to established utilities and reagent supply (D1), it has close-proximity to arterial transport routes (D4), including an established port (D4) at Kwinana and Fremantle, which were both influencing factors when making a decision on the selected location. The site also allows easy future expansion if needed and is in close proximity to construction services, fabrication services (D3) and a skilled labour pool (D1)". Covalent Lithium Commissioning and Technical Manager [34].

2.2 Methods

The enterprises targeted for the research were those located within the KIA because they provided a good cohort of representative industrial enterprises. The research involved mixed methods, designed as an explorative approach which was viewed as being the most appropriate method to be applied to the gathering of data [35]. The research used structured interviews which were suitably flexible to allow for the gathering of quantitative data in relation to the nature of the exchange of materials between enterprises (D1). It also gathered qualitative comment in relation to the degree to which the remaining three KIC4 dimensions were present and their perceived importance to the success of the enterprises surveyed [36]. Prior to the interviews, the research study involved an initial desk top literature review to reconfirm the prominence of the KIA as a mature industrial precinct of international significance, strongly exhibiting the traits of traditional IS (D1) (Fig. 4). In addition, a search was conducted to investigate the extent to which other dimensions of IS were present in the literature [5]. The survey instrument [37] was structured to

Table 1. KIC full members and their substantive product output.

Full member companies	Product output category
Alcoa of Australia	Alumina refining
Avertas Energy[**]	*Waste to Energy (from 2022)*
BP Kwinana	Oil refining (conversion to a renewable energy hub from Mar. 2022)
BHP Kwinana Nickel West	Nickel refining, Nickel and Nickel sulphate
Cockburn Cement	Industrial lime, cement
Covalent Lithium	Lithium hydroxide production (from 2024)
Coogee	Fuel distribution, chemical manufacture and distribution
Chlor-alkali[*]	*Chlorine-based industrial chemicals*
CSBP	Fertilizer and chemical manufacture
Fremantle Ports	Managing and operating port jetties (bulks) and container terminal
Kleenheat	LNG conversion to LPG
Synergy	Electricity generation (LNG-based)
Tianqi Lithium	Lithium hydroxide production (from 2022)
Tronox	Titanium dioxide production
Water Corporation	
Perth Desalination Plant[*]	*Potable water manufacture and distribution (including for industrial use)*
Water Reclamation Plant[*]	*Reclamation of water for industrial process water supply from city wastewater*

[*] Denotes enterprises operating within a KIC Full member parent (respondent) company.
[**] Did not participate.

Table 2. KIC associate members and their substantive product output.

Associate member companies	
Air Liquide	Industrial gasses
BMT Mercury Technology	Waste stream mercury recovery
BOC Ltd	Industrial gasses
Eco Lab	Water, hygiene and infection prevention
Engie	Electricity from LNG and waste gasses
Nufarm Australia	Agricultural chemical production
Sims Metal Management	Large-scale metals recycling and export
Summit Fertilizers	*Fertilizer importation, blending and distribution*
Landmark	*Specialist fertilizer manufacture & distribution*
NewGen Power	*Electricity production from LNG*
Western Energy	*Peaking electricity production from LNG*
Cleanaway	*Waste material aggregation and disposal*
Crushing Services International	*Mining services, heavy fabrication*
DBNGP (WA) Pipelines	*LNG pipeline maintenance and gas distribution*
Programmed	*Labour hire and management*
Freo Group	*Industrial plant hire*
Lanskey Constructions	*Industrial construction services*
RC Construction WA	*Industrial construction services*
Site Sentry	*Site security services*

Table 3. Data adopted from SKM Report (2014) [6] and updated with 2021 data.

Year	1990	2002	2007	2013	2021
Participating enterprises	13	28	31	27	34
Existing interactions (nett)	27	106	145	158	172
New interactions identified	–	79	39	13	21
Interactions discontinued	Not studied	Not studied	Not studied	11	7
Future potential interactions	2	104	86	4	7

gather data (number of, and nature of the material) on the D1 materials exchanged between KIC members, while noting that some of these provide products or services that can be categorised in the posited D2 and D3 categories. The purpose of the research was two-fold. Firstly, to gather data about the number and nature of the exchanges between enterprises, noting that no information in relation to the commercial aspects of the exchanges (prices and volumes/weights) would be obtained as this information was considered commercially sensitive, and thus unlikely to be provided by the respondents. To assist in gaining an insight into the 'reasonable value' of the identified exchanges, it is useful to refer to the SKM 2014 report where this value had been quantified. The inter-industry effect emanating from the KIA enterprises was AUD$9.586 billion [6].

For interpretative purposes, the data was firstly to be converted into a reviewed D1 synergy schematic to assist with gaining an understanding of the extent and complexity of the inter-industry effect (exchanges), and secondly to qualitatively test the extent to which other dimensions were perceived by KIC members to exist.

As part of their studies, a small cohort of Murdoch University sustainable engineering students under the supervision of Dr. Biji Kurup, conducted the interviews and compiled their reports for KIC. A survey questionnaire was prepared (Appendix A) and the interviews were conducted by telephone and email using this survey instrument. Senior environmental managers, operations managers, and Health, Safety and Environment (HSE) managers within the organisations were interviewed [37]. In summary, data collection methods utilised semi-quantitative and qualitative interviews, with manual data entry and analysis via spreadsheet. The data was to be subsequently converted into both a schematic diagram and in a spreadsheet format, where the material exchanged, its sender and receiver could be identified.

Survey questions related to D2 and D4 were designed to elicit indicative data on the extent to which KIC members engaged in the posited broader framework of the KIC4 model. D2 questions were designed to gain an insight into the collective workforce related to the KIA; and the overall requirement for a highly skilled workforce over a lesser-skilled one. The D3 questions were focused on the extent to which there was a reliance for the supply of goods and services from the support industries located adjacent to the heavy industrial area. The D4 questions were focused on the policy and regulatory (government) environment within which the industrial area operates, and KIC members' views about how well it was operating. Additional questions related to the provision of common user infrastructure and its adequacy in relation to impacts on international competitiveness.

3 Results

We have structured this part of the paper to firstly outline the limitations we faced, and subsequently to present the results of the data analysis on D1 to D4, after having introduced those enterprises that participated in the research.

3.1 Industry profiles

KIC's membership at the time of the study was 14 Full members (these are the major industrial enterprises including two substantial subsidiaries) (Tab. 1) and 19 Associate members (Tab. 2), noting that any members not participating in the research are presented in italic font. In total, the number of participants was 20.

Of the KIC Associate members, many fall into the category of not being able to provide materials exchange data because the nature of their businesses is such that they provide services such as engineering, metal treatment, fabrication services, plant or labour hire etc, thus falling into the D3 dimension of IS. Data applicable to non-member enterprises was gathered as a consequence of their engagement in an exchange with a KIC member enterprise. It can be assumed that there was a large number of exchanges attributable to interactions between non-KIC member enterprises and whilst accessing this was outside of the scope of the review, it represents an area for future research. Virgin utility provision (water, electricity, gas) that is reticulated throughout the precinct was not included because their provision is standard throughout most if not all industrial precincts.

The number of industrial enterprises present in the KIA exposes a degree of fluidity. Over the intervening years between the data-recording periods of 2014 and 2021, there have been several company amalgamations, takeovers, additions and closures (Tab. 3). There have also been the ongoing discontinuance or expansion of product (and therefore by-product) ranges by various enterprises, and these are shown as discontinued interactions.

Given the complexity associated with tracking the numerous changes, and that it was the nature of the exchange (sender, receiver, material) that was important

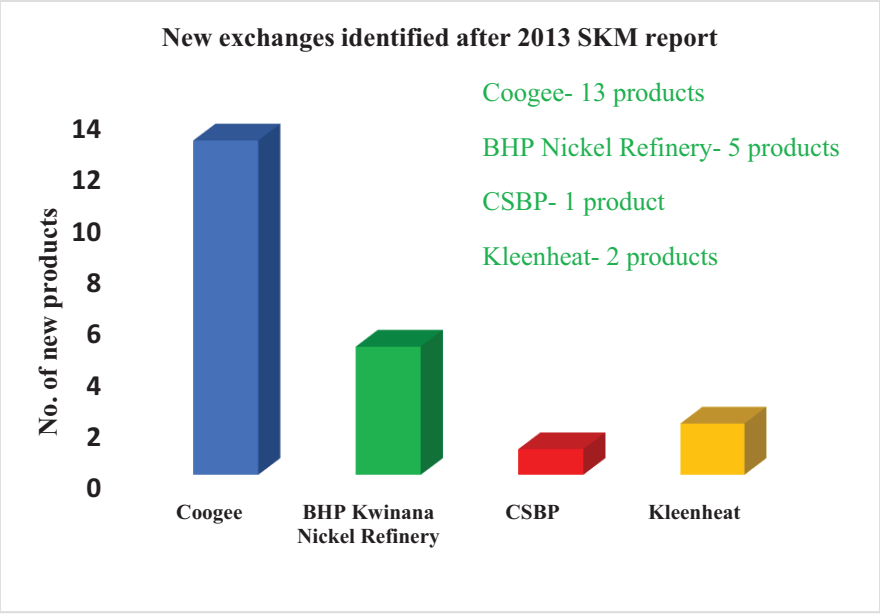

Fig. 5. New materials exchanges identified in the study [38].

to the study, net data were used for reflecting the exchanges relating to participating enterprises. The data in Table 3 serves two purposes. The first is to re-present the exchange data recorded in the years up to 2014 (as presented in SKM 2014) [6], and secondly to add the 2021 data generated as a result of the study. Where exchanges were found to have been discontinued, it was observed that the demand for these materials had either been replaced through product importation, or taken up by existing producers from within the cluster.

Possible new D1 exchanges between enterprises, where identified, were recorded. The existing exchanges were found to increase in net terms from 158 to 172, including the addition of 21 new exchanges since the 2014 study (Fig. 5).

The exchanges are reflected in the schematic (Fig. 6). This is provided to give a sense of the complexity of the exchanges between the enterprises, and is quite unsuitable for detailed study. For this purpose, an expandable digital version is available for download on the KIC website [39].

3.2 Overview of survey results

3.2.1 KIC4 - D1: Product, by-product, and utility synergies

In this section, we have applied the definitions contained in the KIC4 Survey Instrument for commercial products and by-products, where commercial products are purposefully manufactured primarily for sale within the precinct, and where by-products are materials indirectly produced as a result of the manufacture of commercial products. The questions related to this aspect of the survey were put to respondents to determine the extent to which the exchange of materials, utilities and services (Fig. 7) extended beyond the actual WTC, in other words, to gain a broad understanding of the extent to which the KIA was self-reliant and how integrated it was with the broader Western Australian economy.

3.2.1.1 Input chemicals/raw materials

The study confirmed that the input chemicals (raw materials) consumed by the members were predominantly (65%) sourced from within the cluster, and anecdotally, many of the new industrial enterprises attracted to the KIA in recent times are there because their process inputs were able to be sourced locally. There are of course other factors such as the potential for by-product uptake by others, or proximity to utilities and transport infrastructure etc, and this goes to the heart of why the KIA may be so highly regarded as one of the world leaders in traditional IS.

3.2.1.2 Input utilities

The study showed that the input utilities such as water, electricity, and gas, were sourced predominantly from within the WTC. While the LNG pipeline servicing the WTC (and many other consumers) from the gas-fields in the north of WA represents the majority (30%) of the externally-provided utilities for energy production, it also supplies LNG (molecules) for industrial processes. The State-owned water provider (Water Corporation) manufactures potable water (sea water desalination) from within the WTC to provide 17% of Perth's potable water requirements, and also contributes to the supply of industrial process water product for supply to the KIA enterprises. In the context of the study, this virgin potable water is considered a utility. The same organisation collects, treats and disposes wastewater, with 2 of the 5 major metropolitan treatment plants located within the WTC, and some re-purposed waste-water is recycled as high-grade process water back into industry. This water is regarded as a manufactured 'product' for redistribution within the cluster [4,24]. Industrial wastewater collected, treated and disposed by Water Corporation is considered a utility service. Electricity generated for the purpose of distribution

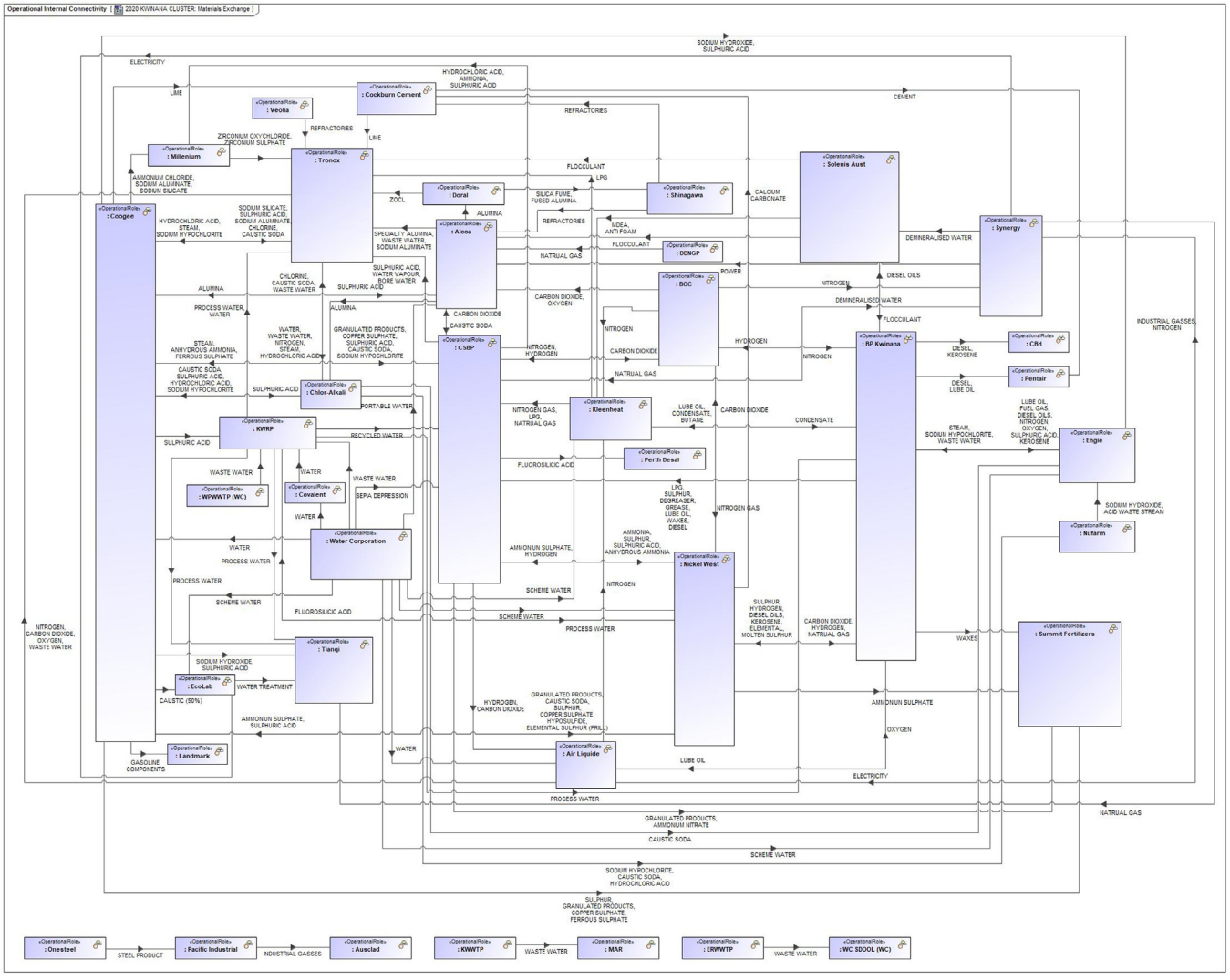

Fig. 6. Industrial symbiosis in Kwinana in 2021 [38].

directly to members was considered to be a utility for the purpose of the study. Energy sources, such as waste heat, steam or gas subsequently converted to electricity for distribution, were considered to be by-products. The major utility providers located within the WTC participated in the survey (Tab. 1).

3.2.1.3 Input services

In this study, respondents identified the extent to which the services they acquire or deliver are located within the WTC. The questions were designed to provide an insight into the efficacy of the KIC4 D3. Of the KIC's 19 Associate members (accurate as at June 2021), five were service providers in the areas of labour and plant hire, fabrication, construction, and engineering services, and all located within the WTC. Within the WTC are numerous non-KIC member service-providing enterprises all being located on the periphery of the 'heavy industrial core', and they were not asked to participate in the survey. Consequently, the data captured in this area was limited, but it was sufficient to indicate that about half of respondents who use external service providers did in fact source them from within the WTC. This provides a strong indication that there is a synergistic proximity relationship between the enterprises located in the heavy industry cluster and the support providing enterprises located on its periphery.

3.2.1.4 Commercial products

The study showed that companies such as Coogee (industrial chemical production and fuel distribution), BHP Nickel West (nickel refinery), CSBP (chemical and fertilizer production), and Kleenheat (LPG refinery) collectively introduced 21 additional commercial products (including refined materials) between 2014 and 2021. This does not impute they simply supplied the same products to more enterprises located within the precinct; they are indeed new product lines created in response to an identified business opportunity. These may have been initiated for example as a result of the input requirements

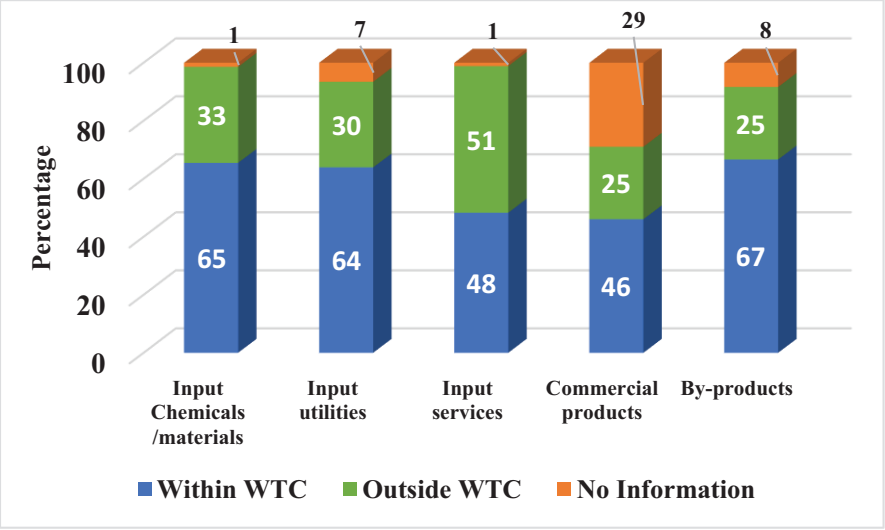

Fig. 7. Relative exchange proportions related to the WTC enterprises surveyed [38].

of new industrial entrants, or perhaps from changed input material availability on the international commodity markets. Conversely, some exchanges were discontinued due to reasons such as product line closures, international competition, enterprise closure, new regulatory requirements leading to unviability, insufficient economies of scale, common-user infrastructure (road, rail, port, pipeline c``orridor) constraints, etc. In a small number of instances, the survey found evidence that a given member had reacted to changed business conditions by both discontinuing an unviable exchange and also developing new ones, indicating the presence of favourable conditions to support the cluster's ongoing organic evolution [40].

A large proportion (46%) of the commercial products manufactured within the WTC were identified as being sold within the precinct (industrial chemicals and gasses, refined materials etc). Whilst a smaller proportion (25%) was identified as being destined for State, national or international markets as finished product, and a further 29% of the commercial products were described as 'destination unidentified'. Further research will be required to reveal product destinations, if indeed acquiring this knowledge is considered desirable, and whilst it can be reasonably assumed that there is a degree of confidentiality in this line of questioning, it is also reasonable to assume that it is likely that all of the products in this latter category are finished product for export beyond the WTC. It is worth noting that new 'value-added' materials production is beginning to emerge from the commercial product range, aside from the traditional staples like alumina and nickel, such as for example high purity alumina and nickel sulphate, both of which are destined for the international electric vehicle battery markets.

3.2.1.5 By-product synergies

Being a central pillar in IS and CE, the by-product exchanges within the KIA were reconfirmed by the findings of the study to be a very important aspect of the KIA ecology, with 67% of them occurring between enterprises located within the WTC. As new enterprises from within the electric vehicle battery industry establish in Kwinana, opportunities for new by-product exchanges emerge. For example, both of the lithium hydroxide chemical production installations under construction will add lithium aluminosilicate residues and gypsum to the inventory of available by-products [41], and the two waste to energy (combustion) plants will similarly add bottom ash, fly ash, and electricity with 50% renewable credits. There is ample opportunity for further study within this dimension, particularly being centred around the various sites that are storing, processing and reusing construction, demolition and process wastes.

3.2.2 KIC4 - D2: Skilled workforce synergy

Questions related to the workforce were designed to gather data on a number of broad characteristics. An industrial cluster's skilled workforce is posited to fall within KIC4 D2, where the totality of the workforce shares a synergistic relationship with the precinct's enterprises. The following quote from a survey respondent supports this view. "*As the* <company name removed> *is a refinery, there is a likelihood that people will be recruited from similar companies within the KIA*".

3.2.2.1 Skilled or unskilled employees

The survey produced a strong response from KIC Full member respondents (75%) toward a preference for employing only people with a defined skill set matched to a given vacancy. We have supplied two quotes to support this data. "*Previous experience in an industrial environment provides exposure to the process and practices for an industrial plant – what is expected regarding HSE (*Health, Safety and Environment*), and knowledge of typical processes. It reduces the time for a person to be fully competent and people will be inherently aware of hazards associated with the workplace*". Also, "*High complexity of*

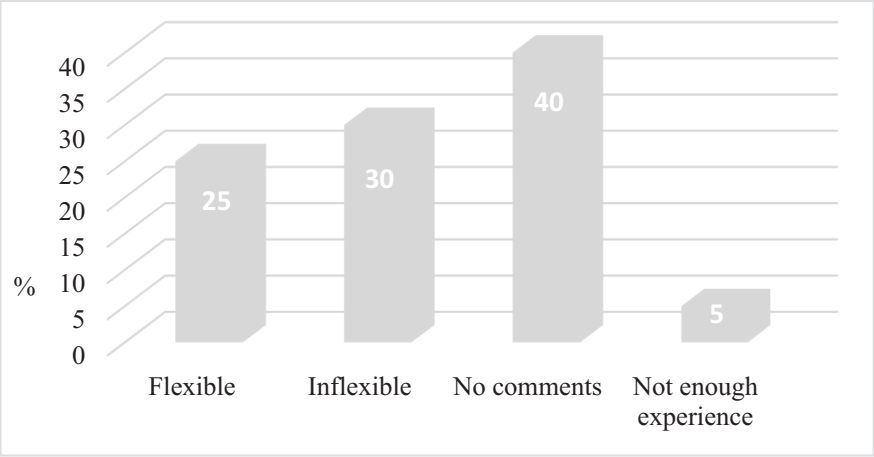

Fig. 8. Survey responses: Legislative framework [38].

<company name removed> *requires specialist skills, knowledge and experience*". The percentage (15%) indicating they would recruit both skilled and unskilled workers indicated a willingness by some to employ lesser-skilled people with suitable attitudinal characteristics, to retrain existing workers into new roles, and to employ apprentices and trainees. It is important to note that many of the KIA enterprises are designated as a 'Major Hazard Facility' by the Regulator, within which there is really no place for low skilled employees other than apprentices under appropriate supervision.

3.2.2.2 Where workers live

The SKM 2014 report identified that two thirds of the KIA workforce (5,000 direct and 26,000 indirect employees) lived within 15kms of their workplace and that this characteristic was valued by the enterprises and workers alike for a range of reasons [6]. A KIC Full member said "*We employ from the local community across a range of skill sets…*". We retested this workforce statistic by asking respondents to provide the postcodes of their employees, with the overall result being that 64% of KIC Full member employees live within 15–20 kms of their workplace, a range reflecting the size of suburban postcodes. It is suggested that collectively, enterprises achieve a more stable workforce, thus tending to avoid expensive recruitment costs, when their workers live nearby as opposed to travelling long distances whilst potentially fatigued after long work-shift day and night combinations.

3.2.2.3 Turnover rate / retention rate

Anecdotally the turnover rate has been broadly described by KIC members as being very low. It was commonplace for workers to have begun their careers as an apprentice or graduate with a specific KIC Full member enterprise, and to have stayed there for their entire working life, and taking promotions throughout. With 10% being broadly regarded as an acceptable turnover rate in an industrial/manufacturing setting, the data from the survey indicated a rate of half of this, at around 5% [42,43]. It can be inferred from this that KIA enterprises collectively share a very stable workforce. Conversely, the retention rate was reported as being very high at around 90%. Whilst the new statistics vary little between 2014 and 2021, there are and have been major influences occurring within the skilled workforce dimension over that period:

- Worker retirements. SKM 2014 reported that around 66% of the KIA's workforce was identified as being within the 'baby-boomer' demographic, indicating a significant risk for industry overall due to the inevitable surge in retirements.
- Advancing technology. The continual introduction of more automated processes puts downward pressure on workforce numbers.
- Economic trends. The drive for efficiency in order to remain internationally competitive has all but eliminated spare workforce capacity within industry, and driven up the use of operational contractors.
- New entrants. As new enterprises are commissioned, they draw their workforce from within the cluster, thus commencing with a skilled workforce most of whom are domiciled locally.

3.2.3 KIC4 – D3: Support industry synergy

In Kwinana's case, the support industry sector is located immediately adjacent to the heavy industrial zone. The data showed that a little under 50% of the services required by heavy industry are located within the WTC, thus confirming the existence of a synergistic proximity relationship between the two industry sectors. The support services identified included civil, mechanical, electrical, dive, pumping, waste collection, engineering, fabrication, labour and plant hire, to name some. While these service providers are geographically part of the WTC, they are clustered adjacent to the KIA. They are not necessarily members of KIC, and there was no attempt to capture the exchanges that occur between them. Anecdotally, the survey revealed the presence of mutually beneficial economic advantages being derived from this proximity

to the KIA's heavy industrial enterprises. The data collected showed that this dimension is strong, and further data collection is needed to reinforce and better define its value.

3.2.4 KIC4 – D4: Governance synergy

Respondents were asked to provide comment on the extent to which they felt the legislative/regulatory framework was sufficiently flexible or supportive of their activities in respect to enabling the creation of new by-product synergy exchanges. The first question, "How flexible or supportive do you feel the legislative framework is in respect to Industrial symbiosis". received a response rate of only 25% which was low relative to the participation rate throughout the survey, with 40% (Fig. 8) declining to comment.

Of the 60% who did provide a comment, almost half of these confirmed that they were experiencing benefit from a flexible framework in respect to IS. At the same time however, a little over half indicated that they regarded regulatory framework as inflexible.

A majority of respondents (40%) did not wish to respond to the question. We speculate this may be an indication that the issue around frustration with the regulatory processes, as highlighted in SKM 2014, had yet to be resolved [6]. SKM reported that while there was some progress in the regulatory governance dimension, there were many major hurdles associated with environmental regulation yet to be overcome for WTC enterprises to be able to have access to some by-products for re-use [4,6]. A written response from one of the members is useful to illustrate this point. "*Controlled Waste Regulations (*Environmental Protection Act*) definition of waste and facilities – restrictive when trying to divert by-products from landfill due to the 'green tape' associated with reclassifying a by-product that is considered to be a waste under the Act*". We observed firstly that members generally felt nervous in expressing their views about the performance of the Industry Regulator, and secondly, that it was a business risk to do so because there could be future repercussions on an enterprise's governance relationship with the Regulator.

The purpose of the second question, "Is there any information/obligation/complexity that you are wanting from any tier of government to be resolved or approved (Local, State or Federal)?", was to explore respondent attitudes in relation to the three layers of government that apply in WA. This question was prepared in an attempt to develop an understanding of industry's views on the perception of 'degree of difficulty' when progressing through the various tiers of government for such things as strategic land use and development planning, environmental approvals, regulatory conditions, legislation/policy development, and provision of common user infrastructure such as roads, rail, port and pipeline corridors. The governance environment of the WTC extends to three local governments, in excess of 13 WA State Government departments, and some (3–5) Federal departments. The majority of survey participants (65%) chose to not provide any comment nor to not raise any issue. The remainder directed their comments to the State tier of government (with one exception toward the local government tier). Issues raised as being of concern included; inadequate buffer zone protection, inflexibility on by-product reuse and transport bottlenecks, overly restrictive controlled waste regulations when trying to divert waste from landfill towards reuse as a by-product, and access costs associated with congested shipping berths. These issues affect all enterprises within the industrial cluster to varying degrees, and all are listed amongst the KIC's seven key strategic issues to be resolved [44]. On this basis we can reasonably assume that those respondents that declined to comment share these issues. We provide a comment from one of the members to illustrate the point that the issues raised are collegiate in nature. "*State government support and solutions are required for providing (*port*) berth access for imports and exports in Kwinana. The two current berths in Kwinana Beach Road* (a common-user cargo jetty) *have reached capacity levels resulting in financial costs* (demurrage and delays) *for customers and general lack of confidence by the market/customers that manufactured goods can be traded reliably and economically*". Of the issues raised, only one response was directed toward the Australian Federal government, and one directed toward Local Government. Dealings with these tiers is usually during the development of a project and so this is unsurprising, however some of the issues more broadly raised do indeed cross over into the Local Government tier.

An updated visual presentation reflecting the contemporary data gathered from the survey D1 exchange diagram was developed and uploaded to the KIC website [31,39], where a PDF version is available to be downloaded. A spreadsheet representation of the exchanges was produced for re-verification by the respondents, and an interactive tabular version was uploaded to accompany the exchange diagram. These graphics may be utilised by those wishing to search for a given exchange material, its sender or its receiver. The KIC had undertaken to review the table periodically, adding or removing exchanges to reflect current practices to provide accurate information to potential new entrants seeking to locate in Kwinana in order to participate in the KIC4 product/by-product exchanges, and for research purposes. The Covalent Lithium refinery, referred to earlier in this paper mentioned an attracting factor for the KIA was the supply of its production reagents, and additionally to the advantages associated with the domiciled skilled workforce, support industries and the common user infrastructure [34]. This company, and similarly other future new entrants, will be able to use the tabular version of the exchanges to locally source their input requirements and to identify potential by-product receivers.

4 Discussion

The research reconfirmed the KIA's continued status as a prime example of traditional IS, or D 1 exchanges, with over 170 exchanges and 34 participating enterprises within that complex industrial cluster. It identified a net increase of an additional 21 new exchanges since 2014, with all of the exchanges being visually expressed (Fig. 6). The data collected confirmed that dimensions 2, 3, and 4 of the KIC4

framework are significant factors based on the responses of the respondents surveyed within the Kwinana cluster. The evidence supports a conclusion that the precinct, as a cluster of domiciled enterprises, positively interacts with, and is well-serviced by, the collective population of skilled workers (D2). We were able to conclude that the relationship between these two collectives is one that exhibits synergistic characteristics, and that it is a strength of the Kwinana precinct that the relationship exists. In a way not dissimilar to that of the conclusion related to D2, the data confirmed that the physical presence of the nearby support industries (D3) in Kwinana, again as a collective, accounted for around half of the services required by the heavy industrial actors. We highlight that as only a small number of support industry respondents were surveyed; we make the observation that the reported proportion of service interactions is likely to be substantially higher. We are therefore able to conclude there is a mature synergistic relationship between the two collectives within the Kwinana precinct (the support industry sector and the heavy industry sector), and that the relationship may be described as synergistic because is considered mutually beneficial. The D4 data gathered presented evidence that the relationship between the public sector actors and the collective of enterprises was a problematic characteristic for the Kwinana precinct. The data showed that 30% of the respondents described the relationship as inflexible, and a further 40% were not willing to provide comment one way or the other. We can conclude therefore that the relationship between the collective of precinct-associated public sector departments/agencies and the precinct's collective of enterprises, whilst mature, appears on the surface, to be poor.

Respondents were broadly of the view that the WTC, and more specifically the KIA itself, was well regarded for its best practice IS (D1), and it was noted that some had plans to include additional D1 exchanges into their operations in the future, again reinforcing the fluidity of the IS environment. The avoidance of the production of waste through its re-classification as a by-product available for re-use as an input material, was seen as being somewhat constrained by the regulatory environment (D4). With the adoption of a more supportive approach by the environmental regulators, current 'waste' could be repurposed to support the CE and fit within the by-product exchange network.

From analysis of the data, it became clear that the respondents recognised the value of IS to their businesses, with benefits extending beyond the mere opportunity for co-location within a precinct. Such additional benefits mentioned by members were broadly related to those associated with broader CE aspirations. They included resource recovery, reduction of waste to landfill (and the associated cost savings from fees and environmental levy reductions), environmental risk reduction, reduction in regulatory or legal compliance costs, and the reputational benefits (by community and government) associated with being perceived as taking responsibility for the management of process by-products through re-purposing waste into a resource [9]. It was clear that IS presented a 'business as usual' approach in the comments provided by the respondents, with it being widely recognised as part of the solution to achieving economic sustainability [45,46]. This aligned with the academic works of Morsleletto and Walker, where they concluded that CE is viewed by industry as being more aligned with the responsible use and management of resources [21,22]. Nikoloau, has expanded the philosophical domain of CE, thus aligning with the theory that governance at all levels has an influence on both circularity and sustainability [20]. Branson in his paper about Kalundborg wrote about the goal of IS being focused toward industrial sustainability, and it being determined by whatever practical outcome that follows the application of the theory [17].

The theory behind the KIC4 model is supportive of Branson's approach, to a degree. The practical outcomes being achieved by industry in Kwinana under the Materials Exchange dimension have their roots in the much-studied field of IS, where the theory has defined the practice. However, the expansion of the single-dimensional IS (D1) into a multi-dimensional approach (D1-4) being described collectively within a single framework is only attributable in a small way in earlier theory. We found no evidence of scholarly work that expanded the conceptual framework of IS to incorporate dimensions in addition to D1. We would posit therefore that in a multi-dimensional IS framework, it is the theory that is emerging from previously un-examined practice. In other words, multi-dimensional IS has been occurring over the years, but not under any pre-defined scholarly framework.

5 Conclusion

The purpose of this paper was to bring forward and test a theoretical framework that would redefine and expand the long-held view that industrial symbiosis is a single-dimensional construct, relating exclusively to the exchange of process by-products to reduce waste. Its objective was to test for the presence of three additional pre-defined dimensions, and if supported by the evidence, to consolidate the proposed four-dimensional symbiosis framework (KIC4). This has been previously conceptualised as an applied process by which any given industrial precinct may be evaluated for its effectiveness against four posited dimensions. To support this, it was demonstrated that the four dimensions could be used as a potential framework for the broader evaluation an industrial precinct for its symbiotic credentials.

The well-accredited Kwinana Industrial Area in Western Australia was selected to be the precinct for the study, which utilised a face-to-face interview process with respondents selected from a cohort of senior managers representing the major enterprises located within the precinct. Data was collected across all four of the KIC4 dimensions (D1: Materials Exchange; D2: Skilled Workforce; D3: Support Industries; and D4 Governance). In addition, observations were made about how the Kwinana precinct was performing against each dimension. It was able to be concluded that symbiotic relationships across D1, D2, and D3 were facilitating a strongly conducive business operating environment for the enterprises located

there, and that the responses associated with D4 were raising issues about a less conducive governance environment. This latter observation being recommended as a source for further enquiry.

The survey instrument was written to gather data to confirm the extent to which respondents were aware of the four posited symbiotic dimensions, and it was concluded that awareness was low. All respondents, however, were able to provide data to indicate that, whilst un-named, the dimensions were characteristics of the Kwinana precinct.

It is expected the outcome of this research will be used in future studies designed to create further knowledge about the validity of the KIC4 expanded IS framework. By this method then, the application of the KIC4 framework has provided a theoretical basis for an expanded conception of industrial symbiosis. Further research is expected build the mechanics of the KIC4 model and seek qualitative and quantitative data to define the concept on a scientific basis. It is expected that application of the model will present a dimensional profile of a given industrial precinct's influencing (constraining and supporting) factors.

The implication of this is that once the status of a brownfield precinct's influencing factors is known, precinct stakeholders will be able to develop improvement strategies. Further, and for those parties with a precinct planning and ongoing management function, the model will provide a means by which a greenfield precinct can be developed to provide a precinct environment that can be highly attractive to its future industrial occupiers. Researchers and other interested stakeholders will be able to identify where the underlying strengths and weaknesses of a given industrial precinct may be found, and in doing so open up the potential for dialogue and pathways towards constraint resolution.

The scale of the operations in Kwinana and the likely extent to which environmental and economic benefits can be locally derived from the dimensional synergies warrant more detailed investigation. Significant research opportunities will arise from the further dissection of each of the four dimensions and from the application of the model once further developed for use as a tool for the design or redesign of industrial precincts around the world.

Abbreviations

CE	Circular Economy
D1, 2, 3, 4	Dimension 1, 2, etc
HSE	Health, safety and environment
IS	Industrial symbiosis
KIA	Kwinana Industrial Area
KIC	Kwinana Industries Council
KIC4	Four-dimensional framework
SKM	Sinclair Knight Merz
WA	Western Australia
WTC	Western Trade Coast

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Conflicts of interest

Mr. Oughton (lead author) is employed as the Director of Kwinana Industries Council.

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Author contribution

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Data availibility

Data are available on request from the authors.

References

1. W.A. Development, *Kwinana Strategic Industrial Area (SIA)*, 2022, [cited 2022 04/02/2022]; Available from: https://developmentwa.com.au/projects/industrial-and-commercial/kwinanasia/overview
2. D. Van Beers et al., Industrial Symbiosis in the Australian Minerals Industry: the cases of Kwinana and Gladstone, J. Ind. Ecol. **11**, (2008). https://10.1162/jiec.2007.1161
3. S. Harris, Mechanisms to enable regional resource synergies, ARC Report: Bulletin No 3, Curtin University of Technology, Perth: Perth, Australia, 2008
4. C. Oughton, M. Anda, B. Kurup, G. Ho, Water circular economy at the Kwinana Industrial Area, Western Australia —the dimensions and value of Industrial Symbiosis, Circ. Econ. Sust. **1**, 995–1018 (2021)
5. C. Oughton, B. Kurup, M. Anda, G. Ho, Industrial Symbiosis to circular economy: what does the literature reveal for a successful complex industrial area? Circ. Econ. Sust. **2**, 1317–1344 (2022)
6. Sinclair Knight Merz (SKM) & Resource Economic Unit (REU), *Western-trade-coast integrated assessment, environmental, social and economic impact* (Perth, Australia, 2014)
7. D. van Beers, Capturing regional synergies in the Kwinana Industrial Area - 2006 status report, Centre for Sustainable Resource Processing, Curtin University 2006, Perth, Australia, 2006
8. Government of Western Australia, WESTPORT: future port recommendations, stage 2 report, 2020
9. B. Kurup, D. Stehlik, Towards a model to assess the sustainability implications of Industrial Symbiosis in Eco-Industrial Parks, J. Prog. Ind. Ecol. **6**, 103–119 (2009)

10. Dames and Moore, *Kwinana heavy industry economic impact study* (Confederation of Western Australian Industry, 1990)
11. Sinclair Knight Merz (SKM), *Kwinana Industrial Area economic impact study: an example of industrial interaction* (Perth, WA, Australia, 2002)
12. Sinclair Knight Merz (SKM), *Kwinana Industrial Area economic impact study: an example of industrial interaction* (Perth, WA, Australia, 2007)
13. D. Lombardi, P. Laybourn, Redefining Industrial Symbiosis, J. Ind. Ecol. **16**, 28–37 (2012)
14. R. Taddeo, A. Simboli, G. Ioppolo, A. Morgante, Industrial Symbiosis, networking and innovation: the potential role of innovation poles, J. Sus. **9**, 169 (2017)
15. T. Tudor, E. Adam, M. Bates, Drivers and limitations for the successful development and functioning of EIPs (eco-industrial parks): a literature review, J. Ecol. Eco. **61**, 199–207 (2007)
16. D. Sakr, L. Baas, S. El-Haggar, D. Huisingh, Critical success and limiting factors for eco-industrial parks: global trends and Egyptian context, J. Clean. Prod. **19**, 1158–1169 (2011)
17. R. Branson, Re-constructing Kalundborg: the reality of bilateral symbiosis and other insights, J. Clean. Prod. **112**, 4344–4352 (2016)
18. M. Chertow, Industrial Symbiosis: literature and taxonomy, Ann. Rev. Energy (n. a.) Environ. (a) **25**, 313–337 (2000)
19. B. Kurup, Methodology for capturing environmental, social and economic implications of Industrial Symbiosis in heavy industrial areas, in: *Centre for Excellence in Cleaner Production*, 2007, Curtin University, Perth, Australia,
20. I.E. Nikolaou, N. Jones, A. Stefanakis, Circular economy and sustainability: the past, the present and the future directions, Circ. Econ. Sust. **1**, 1–20 (2021)
21. P. Morseletto, Targets for a circular economy, Resour. Conserv. Recycl. **153**, 104553 (2020)
22. A.M. Walker, K. Opferkuch, E. Roos Lindgreen, A. Simboli, W. J.V. Vermeulen, A. Raggi, Assessing the social sustainability of circular economy practices: industry perspectives from Italy and the Netherlands, Sust. Prod. Consum. **27**, 831–844 (2021)
23. Regional Development Australia (Perth), K., Henderson Alliance, Li Valley Inc., *Enabling the WesternTradeCoast. 2020*, 2020, Australia
24. S. Harris, R. van Berkel, B. Kurup, Fostering Industrial Symbiosis for regional sustainable development outcomes, in: *CRRC 2008*, 2008, Queen's University, Belfast
25. A. Velenturf, Analysing the governance system for the promotion of industrial symbiosis in the Humber region, UK, J. People, Place Policy (a). **10**, 146–173 (2016)
26. B.H. Roberts, The application of industrial ecology principles and planning guidelines for the development of eco-industrial parks, an Australian case study, J. Clean. Prod. **12**, 997–1010 (2004)
27. A. Golev, D.G. Corder, P.D.P. Giurco, Barriers to Industrial Symbiosis: insights from the use of a maturity grid, J. Ind. Ecol. **19**, 141–153 (2015)
28. Government of Western Australia, *Waste Avoidance and Resources Recovery Act*. 2007, Department of Environment & Regulation
29. S. Harris, *Regulatory and Policy Issues of Regional Synergies in the Kwinana Industrial Area: A Scoping Study: Bulletin No 2*. 2007, Centre of Excellence in Cleaner Production, Curtin University of Technology
30. Government of Western Australia, *Assessing whether material is waste: Fact sheet*, Department of Water and Environmental Regulation, Editor. 2017, Department of Water and Environmental Regulation, Perth, Australia
31. Government of Western Australia, *Closing the loop - waste reforms for a circular economy: consultation paper*, 2020
32. Government of Western Australia, *Waste not, want not: valuing waste as a resource*, 2021
33. Government of Western Australia, *Waste not want not: valuing waste as resource, proposed legislative framework for waste-derived materials. 2020, Department of Water and Environmental Regulation.*, 2020, Department of Water and Environmental Regulation, Perth, Australia
34. Kwinana Industries Council (KIC), *Kwinana's Lithium Valley ticks all the boxes for new resident – WA*, in *The West Australian*. 2021, Perth
35. U. Flick, *An introduction to qualitative research*, 6th ed. (SAGE, London, 2018)
36. W.C. Adams, *Conducting semi-structured interviews*, in: H. H.P., K.E. Newcomer, L.S. Wholey, (Eds), *Handbook of Practical Program Evaluation*, 2015, John Wiley & Sons, Ltd. pp. 492–505
37. C. Oughton, *Survey Instrument for the 2020 Industrial Symbiosis review and initial assessment of KIC4 Dimensions 2,3, and 4.* 2021, Kwinana Industries Council, Perth, Australia. Available at https://kic.org.au/wp-content/uploads/2020/2023/07/Materials-exchange-survey-instrument_RS_2023-1.pdf
38. Kwinana Industries Council (KIC), *Industries & Synergies*, 2020 (b); Available from: www.https://kic.org.au/industry/synergies
39. Kwinana Industries Council, *Kwinana Industrial Symbiosis Project-update*, 2021, KIC, Perth, Australia
40. Reutors events, *BP, Macquaris study green hydrogen hub concept in Western Australia*, 2021. Available from: https://www.reuters.com/business/sustainable-business/bp-macquarie-study-green-hydrogen-hub-concept-western-australia-2021-09-07/
41. A. Karrech, M. Dong, M. Elchalakani, M.A. Shahin, Sustainable geopolymer using lithium concentrate residues, Constr. Build. Mater. **228**, (2019). https://10.1016/j.conbuildmat.2019.116740
42. Australian Human Resources Institute, *Turnover and research retention report*, 2018
43. C. Oughton, *Lithium mine to market, Australia 2020: the dimensions and value of Industrial Symbiosis*, 2020 [cited 2022 06/02/2022]; Available from: https://kic.org.au/library/media-presentations/
44. Kwinana Industries Council (KIC), *Key strategy issues*, 2022 [cited 2022 04/02/2022]; Available from: https://kic.org.au/industry/key-strategic-issues/
45. S. Harris, The potential role of Industrial Symbiosis in combating global warming, in: *International Conference on Climate Change*, 2007, Hong Kong
46. World Economic Forum, *Industrial clusters: working together to achieve net zero*, 2020

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Appendix A

Survey instrument for the 2021 Industrial Symbiosis review and initial assessment of KIC4 dimensions 2, 3 and 4 - preamble

The Kwinana Industries Council (or KIC), is updating the Industrial Symbiosis schematic. The attachment (attach the 2014 schematic) shows an image of the most recent one which was compiled using 2013 data and published in 2014.

KIC is undertaking the review in partnership with Murdoch University utilising several Engineering Masters students under the supervision of Adjunct Professor Dr. Biji Kurup, of Murdoch University.

The first version of the schematic was produced in 1992. This review will be the 5th in the ongoing series. Previous reviews have been limited to gathering data about products and by-product use. This review will include these exchanges and will extend to include the provision of utilities and services such as labour and plant hire, fabrication, construction and engineering services.

It is an important undertaking especially currently, because many new industries are looking to enter the industrial area and are looking for suppliers of inputs and receivers of outputs (or by-products).

The students have a series of questions to be asked about your company. The questions have been endorsed by the KIC Director, Mr. Chris Oughton. You are encouraged to include input and output material supply chains beyond the membership of the KIC.

Definitions

KIC:	Kwinana Industries Council
WTC:	Western Trade Coast
Products:	Commercial products directly manufactured for sale, the purpose of the process.
By-products:	Materials indirectly produced as a result of the manufacture of commercial products

Questions:

Product, By-product and Utility Exchanges synergy (sample data table below)

1. What is the name of your company and are they a member of Kwinana Industries Council?
2. Does the company exist to:
   a. Produce or distribute **product** for sale.
   b. Provide **services** such as construction, fabrication, engineering, plant or labour hire.

   If the company responded to 'a' above, answer the questions 3–12

   If the company responded to 'b' above, please answer the questions under the heading 'Secondary Industries Synergy.
3. What are the **products** you produce or distribute:
4. What **input chemicals or other materials** do you acquire for your production:
   a. For each,
      i. From which company is the material sourced:
      ii. Identify each of the suppliers and the contact role:
      iii. Is the supplier located within the WTC, and if not, where:
5. What **input utilities** (water <identify if it is potable water or recycled water>, electricity, steam, gas) do you acquire for your production:
   a. For each,
      i. Identify each of the suppliers and the contact role:
      ii. Is the supplier located within the WTC and if not iii. where:
6. What **input services** do you acquire for your business, and from whom:

   This question refers to the provision of services such as labour and plant hire, fabrication, construction and engineering services).
   a. For each,
      i. Identify each of the suppliers and the contact role
      ii. Is the supplier located within the WTC, and if not,
      iii. where:
7. What are the company's **commercially manufactured products** (outputs):
   a. List these and for each, identify if they are sold to buyers within:
      i. The State of Western Australia, identify the company
      ii. States or Territories within Australia, identify the State or Territory
      iii. International markets, identify the country
8. Does the company **produce by-products**? (Chemicals, materials, or utilities such as water, electricity, steam, gas)
   a. List these and for each, identify what happens to them:
      i. Are they stockpiled, and if so where:
      ii. Are they provided to another company, for use in their own production process:
      iii. Does the exchange provide a net income stream for the by-product producing company:
9. Does the company **receive by-products** from another company? (Chemicals, materials or utilities such as water, electricity, steam, gas) from another company:
   a. List these and for each, identify if they are received from companies within:
      I.The Western Trade Coast, identify the company:
      ii. The State of Western Australia, identify the company:
      iii. From outside WA:
10. Are there any future product or by-product exchanges that you are working on or which you would like to develop? Can you share the nature of these please:

The following two questions relate to the Governance synergy

11. How flexible or supportive do you feel the legislative framework is in respect to Industrial symbiosis?
12. Are there any information/obligation/complexities that you are wanting from any government stated below to be resolved or approved?
a. Local government
b. State government
c. Federal government

The support industry synergy

These questions are for companies located within the Western Trade Coast that provide services such as labour and plant hire, fabrication, construction and engineering services
13. What services do you **provide to companies** located within the WTC:
a. List these and for each identify the client company within the WTC:
b. List clients within the WTC that you have provided services to:

The skilled and experienced workforce' synergy

The next questions relate to a company's propensity to hire from within the local skilled and experienced workforce, be this managerial, professional (engineers, scientists etc), trades, administration etc. The local workforce is defined as those already working within the industrial area. These questions are focusing on the 'Skilled and Experienced Workforce' synergy.

14. With the exception of employees that are required to have highly specialised engineering or scientific backgrounds, does your company have a preference for employing appropriately skilled and experienced people from within the existing industrial workforce?
a. If yes, please explain:
b. If no, please explain:
15. What proportion of your workforce live within 15–20 kilometres of their workplace? Could we obtain a list of employee post codes:
16. What is the company's employee turn-over rate and retention rate?

The next questions are for companies looking to come into the WTC
17. **Name** of the company and a **contact person** for future inquiries:
18. What is the **product** (or products) the company will produce:
19. What **input materials and utilities** will the company's processes need:
a. For each, from where will they be sourced:
20. What **by-product outputs** will the processes produce?
21. Would you like to be placed on a **public database** for companies looking to enter the Western Trade Coast, to assist with input materials and utilities, and process by-product destinations?