Industrialisation, Ecologicalisation and Digitalisation (IED): Building a theoretical framework for sustainable development

Abstract

Purpose - In the past two decades, manufacturing has witnessed significant transformations alongside ecological challenges. Meanwhile, industrial 4.0 digital technologies have accelerated industrialisation with potentials of innovation in the context of circular economy. However, current concepts and models are fragmented and impractical. Our paper aims to develop a holistic view integrating the three bodies of knowledge - industrialisation, ecologicalisation, digitalisation (IED) - in order to achieve sustainable development.

Design/methodology/approach - Critical literature review is conducted across three bodies of knowledge. Key themes are summarised with the identification of research gaps. A theoretical framework is synthesised and developed aiming to achieve synergy from IED with the modules, integration architecture, mechanism, and dynamic paths.

Findings - First, we review and develop three conceptual models of ecologicalised industrialisation (IE^3), industrial system digitalisation (D_1), and digital technology industrialisation (D_2) separately. Second, we propose a theoretical framework seeking to synthesise the above three conceptual models together to form the IED. Third, we design a process orientated abductive approach to improve and validate the IED framework.

Originality - This study contributes to the limited literature addressing the linkage of IED by integration different perspectives to develop theory in a novel way. Practically, it provides important tools for organisations to consider resource cascading in combination with digitalisation during the industrial system design.

Keywords: Industrial ecology, Industrial system, Circular Economy, Digitalisation, Sustainability

1. Introduction

In the past two decades, manufacturing has witnessed significant transformations from factory-based operations to international dispersed networks, vertical collaboration among supply chain partners, and business ecosystems (Shi and Gregory, 2005, Shi et al., 2021). Nevertheless, the global industrialisation process is now more subject to the requirements and constraints of environmental protection. China for example, via reform and opening practices has rapidly realised industrialisation through gradual integration into global marketisation. However, problems such as intense pollution treatment due to high-intensity industrialisation make the balance between industrialisation and ecologicalisation unsolved (Shi et al., 2021). At national level, this kind of development pattern should not be repeated in the future. Instead, new approaches that consider the balance of environmental and business ecosystems should be used as an essential reference for the industrialisation of other countries such as Vietnam and Brazil. At an organisational level, issues such as the ecological requirements in the process of industrialisation and the consideration of ecological problems in advance when designing the production system have become increasingly important. There are concepts such as circular economy addressing broader issues in response to socio-environmental challenges (Ghisellin et al., 2016), yet in practice how to consider the ecological requirements in the process of industrialisation and how to consider the ecological problems in advance when designing the production system need to be solved.

Industrial 4.0 technologies, artificial intelligence (AI), robot, big data, and Internet of things (IoT) has accelerated industrialisation via better efficiency and effectiveness (Kiel et al., 2017; Sung, 2018; Lanzolla et al., 2020). This change requires the enterprises' R&D, design, and production departments to respond quickly to the ever-changing demands from both market and external factors such as the natural environment. In practice, novel business models only truly evolve in a digital environment. For example, Alibaba has utilised digital technologies that encompass resource allocation at the organisation and business ecosystem levels. Nevertheless, many companies (especially SMEs) are facing the anxiety and pressure of choices without knowing which technology is effective and should be promoted first; this has caused confusion when attempting to take advantage of opportunities. Thus, a clear guide addressing the co-evolution and synergy of Industrialisation, Ecologicalisation and Digitalisation (IED) is needed.

This paper attempts to develop a theoretical framework that aims to integrate the IED for sustainable development. There is no existing holistic theoretical model that integrate industrialisation, ecologicalisation, and digitalisation. Therefore, rather than comparing with existing models, the paper draws upon the literature across the three areas respectively to generate a completely new framework and proposes a research agenda alongside methods to advance the theory (Post et al., 2020). The specific objectives are:

- To explore the themes of IED, and develop a theoretical framework to integrate these three aspects;
- To propose an abductive method with process-oriented approach to further enrich and validate the theoretical framework;
- To promote the research agenda, where researchers can develop proposals and projects tailored to local needs.

To achieve the objective, we first conducted a critical literature review and followed the example set by Campbell-Johnston et al. (2020) to identify and synthesise knowledge for the aim of generating new theoretical models (Grant and Booth, 2009; Campbell-Johnston et al., 2020). We reviewed all three relevant theory groups to capture: 1) ecologicalised industrialisation (IE^3), 2) digitalisation of industrial system (D_1), 3) the Industrialisation of Digital Technology (D_2). Of potentially 300 articles published in Scopus and Business Source Premier database since 2010, we chose around 110 papers with large amounts of citation and focused on the in-depth interpretation of the predominant concepts (Appendix 1, 2, 3). It covered industrial system, circular economy, industrial symbiosis, digital transformation, and Industrial 4.0 technologies, which are important theoretical building blocks. We then interpreted meanings, evolution path, critical stages, and linkages among the concepts. Themes are categorised (Grodal, Anteby and Holm, 2021) along with their connections conceptualised and confirmed among the research team. Finally, we generated an integrated theoretical framework, illustrating it through discussion and a case observation from theory and practice perspectives.

The remainder of the paper is structured as follows. Section 2 and 3 introduce the relevant literature and summarise the key themes. In Section 4, a theoretical framework regarding the synergy of IED is proposed, followed by a case observation and discussion. Section 5, proposes a process orientated abductive research method, based on the framework, which is followed by a research agenda and conclusion. Our paper contributes to the limited literature addressing the linkage of IED by integrating different perspectives to develop theory in a novel way. Practically, it provides important tools for organisations to consider resource cascading in combination with digitalisation during the industrial system design.

2. Ecologicalised Industrialisation: towards IE^3

This section reviews the concepts and evolving paths of ecologicalised industrialisation, eventually building a framework of IE^3. Full reference of the literature is summarised as Appendix 1.

2.1 Industrialisation and Emerging Challenges

Industrialisation has multiple meanings and levels. Macro wise, it has more implications for the transformation process on national industrial structures such as transitioning from an agricultural society towards an industrial society (Chang, 1949; Kiely, 1998; Pomeranz, 2001). Micro wise, there is emphasis on the formation and development process from scratch or transitioning from a small industry towards a mature industry; an example is the current digital technologies undergoing the commercialisation journeys towards emerging industries (Rogers, et al, 2004; Datta, et al, 2013). In between that is the more interesting meso-level, where industrialisation implies industrial system design, construction, operations, and improvement (Slack et al., 2016).

Contrasting to industrialisation research, its outcomes – the industrial systems – are largely neglected and fragmented due to its diversity and difficulty in generalisation. According to the Royal Academy of Engineering (2012), "*An industrial system includes the context, resources, activities, processes, actors, and interdependencies that support the creation and delivery of products and services. A clearer understanding of industrial systems - a holistic view - can identify those 'levers' which are available to generate and, crucially, capture value"* (p.8). Industrial systems have evolved into various kinds of network-based relationships from the traditional input-output transformation model during the globalisation in the last forty years. Multinational corporations have attempted to globalise their geographically dispersed factories by coordinating them into a synergetic network (Flaherty, 1986; Ferdows, 1997; Shi and Gregory, 1998). This transformation has driven basic industrial functions and effectiveness from product-based competitive advantages towards network strategic capability developments, driving industrial systems beyond the factory wall & the strategy beyond product focus.

Besides MNCs' international expansions, it has become more popular for companies to downsize and outsource their non-core business tasks and to set-up inter-firm collaborations (Lambert, et al, 1998; Lamming et al., 2000; Brewer, et al., 2001). This development has pushed manufacturing systems into a new relationship beyond the traditional concept of the firm owning and internally operating their factories. A company may now only own a small portion of the supply chain but can still strategically co-ordinate or integrate the whole supply chain to deliver a competitive product to market. Equally interesting is that there are increased observations on geographic clustering emerging worldwide (Piore and Sabel, 1984; Porter, 1998). The clusters are a different form of supply networks – some are internally self-sufficient in a region while others are virtually integrated with other clusters. These new supply networks demonstrate that inter-firm collaborations have emerged as a new type of industrial system.

Combining both developments, as Figure 1 illustrates, a new type of industrial network can be derived with the characteristics of international and inter-firm relationships. The combination provides a new operational environment for industrial system to access, optimise, and operate its strategic resources.

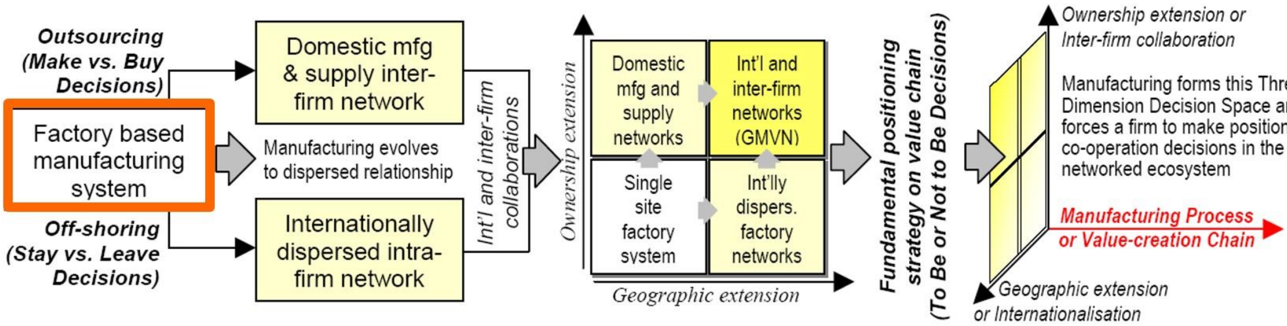

Figure 1. Industrial network featuring internationalisation and inter-firm relationships

During business globalisation, China has caught up and emerged as one of the largest industrial nations. Despite the macro-level achievement in China, with a nurturing business ecosystem including all kinds of industrial infrastructures and a readiness for embracing new technologies and innovative ideas, severe challenges are observed at meso and micro levels in terms of the negative impact on the natural ecological environment (Shi et al., 2021). These significant impacts have impacted climate change (Masson-Delmotte et al., 2021), water (Owa, 2013), soil (Mishra et al., 2015), and many others. The greater the advantage, the greater the damage; the environmental and ecological crisis has become one of the biggest challenges to the world's continuous development. New ways to achieve a more balanced development between industrialisation, environmental protection, and resource efficiency is needed (Shi et al., 2021).

2.2 Ecologicalisation of Industrial Systems

The current industrial system models are not sustainable for further development if considering the environmental impact (Evans et al., 2009). To tackle the increasingly serious contradiction between economic development and environmental protection, industrial symbiosis or its extended version– circular economy, has stepped into the centre of researchers' focus (MacArthur, 2013). Industrial ecology is a study that focuses on production systems with respect to nature, where it attempts to mimic the natural ecosystem by conserving and reusing resources with the ideal of having no waste (Valenzuela-Venegas, et al., 2016). It aims to increase business success through increased economic gains while preserving the environment and considering the social aspect of the system (Chertow, 2007). Industrial symbiosis is a subset of Industrial ecology and attempts to realise those goals by forming symbiotic relationships between different organisations/industries via their wastes and/or by-products. Participating industries vary, including chemical (Mannino et al., 2015), manufacturing (Harris and Pritchard, 2004; Zhu et al., 2007), waste management (Mirata and Emtairah, 2005) and oil & gas (Wang et al., 2019) and so forth. The impacts of industrial symbiosis are also frequently discussed, with focus on environmental benefits (Daddi et al., 2017), economic benefits (Cao et al., 2018) and social benefits (Valenzuela-Venegas et al., 2016).

Circular Economy is closely related to industrial ecology and symbiosis, it aims to create a closed loop system via the continual use of resources. These methods include reusing, recycling, repairing, remanufacturing, sharing, and refurbishing (Geissdoerfer et., 2017). This process will reduce the creation of waste and reduce carbon emissions & pollution, ultimately minimising the resource inputs required to produce goods and run services. It is also like industrial ecology and symbiosis in its attempt to help businesses succeed without damaging the environment or affecting the quality of life of the involved organisations (Baldassarre et al., 2019).

Another concept similar to industrial symbiosis and circular economy beyond the scope of industrial systems is the industrial ecologicalisation research of Urban Industrial Symbiosis (UIS). UIS is the synergy and symbiotic relationships between industrial and urban areas that aim to scale up the efficiency of the previously mentioned benefits while increasing its scope in mitigating problems regarding sustainability, pollution emissions, resource consumption, and waste treatment (Dong et al., 2016). The idea of UIS has been around since the 1980s (Kurdve et al., 2018), but the concept was only further developed and reinforced from 1997 to 2006 through eco-towns via its proximity with industrial zones (Van Berkel et al., 2009). However, only in recent years have the number of publications regarding UIS started to grow (Neves et al., 2020). This was due to how saturated the industrial symbiosis topic is and its growing popularity, due to the benefits, despite its complexity.

2.3 Resource Cascading for More Sustainable Development

As an input-output system, an industrial system will not only produce many types of by-products that industry symbiosis aims to tackle but also consume various kinds of raw materials that can potentially be optimised based on their intrinsic properties. Resource cascading, as an emerging research area and a body of knowledge, specialises in exploring the value creation potentials of resources including energy. Pioneered by Sirkin and ten Houten (1994) from Netherlands, Cascade chain is suggested in order to develop a systematic methodology as "*a theoretical notion which integrates concepts of resource economy and sustainability into an operational framework for determining the efficiency and appropriateness of a given resource exploitation in a given context*" (p.215). It has been recognised as "*a method for optimizing resource utilization through a sequential re-use of the remaining resource quality from previously used commodities and substances*" (Sirkin and Ten Houten, 1994, p.215).

Research into cascade chains has a historical association with developing interconnected wood, food, energy & nutrient chains, and industry ecology (Mair and Stern, 2017; Olsson et al., 2018). General implementation in a wider range of industries have potential challenges. For example, there are no specific roles that consider the resource potentials and their optimised utilisations. Kieran Campbell-Johnston et al. (2020) also complain there is no specific knowledge and framework for conducting the resource cascading process. Therefore, they explore and develop an integrated framework combining circular economy approaches and the cascading process together (Campbell-Johnston et al, 2020). It is a clear direction for many professionals to combine the various circular economy approaches with cascading process in the whole value creation process or supply chain.

2.4 IE^3 Integrated Model

Each of the above key concept, industrialisation, industrial systems, ecologicalisation including circular economy, industry symbiosis & decarbonisation, and resource cascading, has been more or less explored and developed to solve operational problems. However, the concepts and related processes are still fragmented. An integrated framework is critical because it not only benefits the practitioners by providing the systematic and comprehensive process with tools and techniques for solving the problems but also, more importantly, lay down a solid foundation for knowledge accumulation and new discipline development. Figure 2 seeks to integrate the above concepts together to combine the business and natural ecosystems together to gain synergy (Shi et al., 2021). It pushes the main concepts towards the process-oriented modules and tries to achieve three principal functions - designing an industrial system through the business ecosystem approach; optimise resources through the resource cascading process; and achieve industrial symbiosis through the industrial ecology.

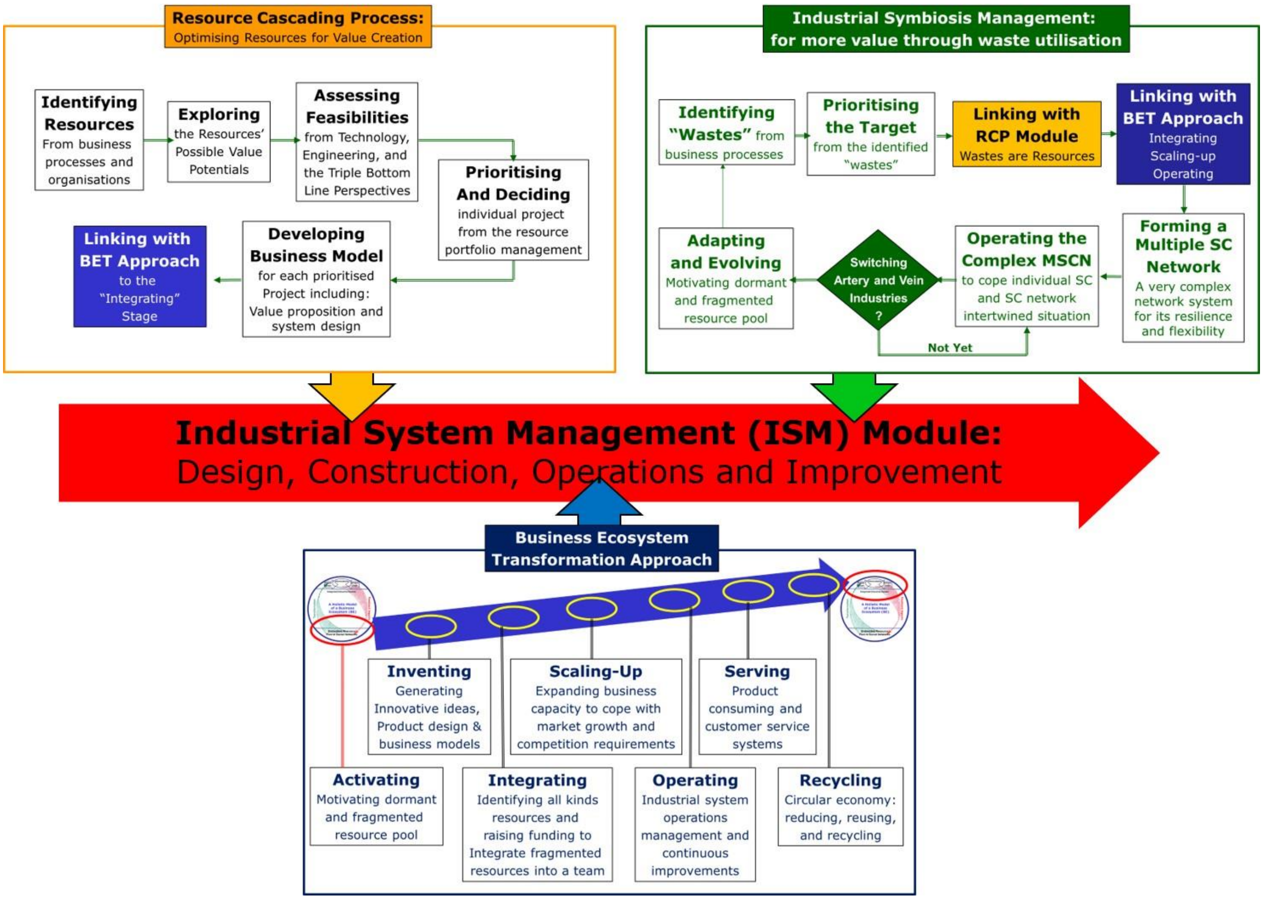

Figure 2. IE^3 integrated process framework
Source: Shi et al., 2021

Nevertheless, there are limitations of the IE^3 framework (Figure 2). First, it does not cover the whole life cycle of the industrial system development. It highlights the design and construction process but ignores post design process – operations and continuous improvement. It also needs to enhance the recycling phase during or after the servicing phase via the several-Rs. Second, decarbonisation in the industrial system and its life cycle has not been integrated into the framework, which leaves a large hole for environmental protections and improvements. Finally, a key driving force for industrial system developments, technology or more specifically digital technology has been neglected causing the IE^3 framework to have a fatal weakness in coping with current industrial demands.

Based on this, a new simplified IE^3 (Figure 3) can highlight the core industrial system development process, as the industrialisation process, from creative idea generation to new generation of industrial system through design, construction, operations and improvement. During the industrialisation process journey, the IE^3 model also provides three key functional modules – IE$_1$ improves resource efficiency; IE$_2$ reconfigures resources into industrial system more effectively and efficiently; and IE$_3$ reduces the environmental impacts of industrialisation. Under the three module supports, industrialisation is expected to be not only more effectively developed and operated but also more sustainable and environment friendly.

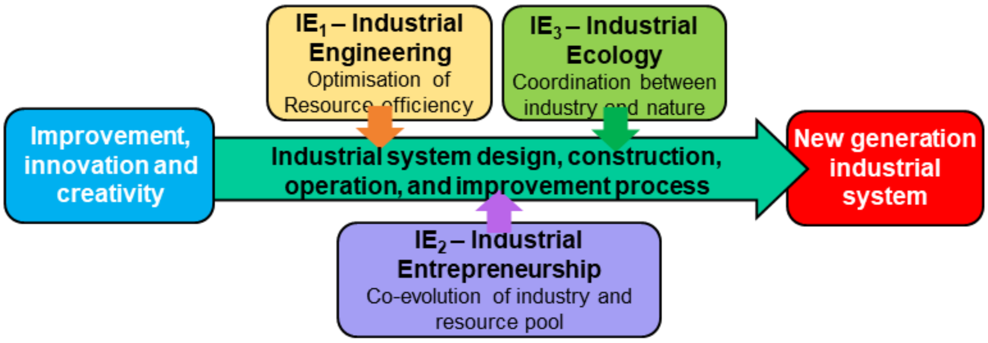

Figure 3. A concise IE^3 model to support new industrialisation

3. Digitalisation: its position in industrialisation and ecologicalisation

This section reviews the concepts of digitalisation, in terms of D_1 – digitalisation of industrial system, and D_2 – the industrialisation of digital technologies. Full reference of the D1 literature is summarised as Appendix 2, and full reference of the D_2 literature is shown in Appendix 3.

3.1 D_1: Digitalisation of industrial system

A primary concept of digitalisation concerns the digital transformation of industrial system (D_1). Industrial ecology and industrial system ecologicalisation have brought in researcher's interest for a few decades. Digital technology, as an enabling tool, has recently been embedded to improve or extend the goal of ecologicalisation (Moreau et al., 2021). For single factory, Matsuda and Kimura (2015) proposed the digital eco-factory to enhance eco-efficiency. Ma et al. (2020) suggests a data-driven framework at factory-level for improvement in energy-intensive industries. From the technical perspective, Tsai et al. (2019) applied the IoT techniques to assist activity-based standard costing implementation in the manufacturing execution system. However, there is still limited research focusing on digitally managing the flow of material and energy digitalisation. The discussion of extending from a single site to the whole product life cycle has garnered a lot of attention. Moreau et al., (2021) argue that the Information and communications technologies (ICTs) need to help systems improve beyond energy efficiency goals and be mindful of their indirect impact, additionally new business model systems embedded with ICT need to be transformed and not just optimized. Ferrari et al. (2021) linked life cycle assessment with life cycle inventory and enterprise resource planning via the case of a ceramic tile manufacturer. Regarding the environmental impact of digital products, researchers argue that it may not necessarily perform better than physical companions. Another important dimension of industrial ecologicalisation is industrial symbiosis. Digital technology has provided several supports to enhance the symbiosis efficacy. A research-spinoff company Symbiosis builds up big data analytic systems for detecting potential symbiosis links in North and Central Greece (Dalamagas et al., 2020; Dounavis et al., 2019). Other countries such as Italy also has its unique digital platforms for industrial symbiosis (Pizzi et al., 2021). With a focus on industrial solid waste, a similar but larger scale digital platform is built in collaboration with 500 plants across four countries (Angelis-Dimakis et al., 2021). Data analysis on industrial symbiosis information databases can also be useful to identify insights (Jato-Espino and Ruiz-Puente, 2020). Combining multiple technologies including IoT, 5G, AI and blockchain, Teng et al. (2021) analysed the potential of digital-twins for future industrial energy savings. In general, related studies confirm that the benefits to achieving industrial symbiosis via digital technology require better algorithms to analyse energy and material flows while considering new resources for symbiosis are in need. Expanding beyond plants and industrial symbiosis, circular economy is regarded as a boarder concept of implementing ecologicalisation to the whole society. There are increasing amounts of research discussing the topic of digital technology as an enabler to circular economy. Rajala et al. (2018) used cases to demonstrate how digital technologies boost the sustainability of industrial ecosystem in three archetypes. Digital-twin is also proposed for multiple product-life remanufacturing (Wang et al., 2020). Researchers also considered implementing circular economy in an urban environment by leveraging digital technologies including real-time water monitoring and digital camera for traffic flow control (D'Amico et al., 2021). Nogueira et al. (2019) argues that digitalisation is more than an enabler and is one of the important capitals in forming circular economy along with natural, financial capitals, etc. Avila-Gutierrez et al. (2020) pushed even further and stated that the digital transformation of business can upgrade circular economy to multilevel and multiscale level. In summary, integrating digitalisation and industrial ecologicalisation is still an up and rising interdisciplinary field that requires more research for thorough understanding.

Industrial systems have a long history of applying digital technology to improve operational and managerial efficiency. However, the recent accelerated and substantial booming of new digital technology applications have dramatically fastened the process of industrial system digitalisation (Oztemel and Gursev, 2020). From the new technologies perspective, there are several major ICT tools to empower industrial system for better performance. IoT is forming a network of different physical devices to collect, accumulate, process data, & perform actions and is regarded as one of the major enabling technologies for industrial system digitalisation (Al-Fuqaha et al., 2015; Bello et al., 2017; Burke et al., 2013; Ge et al., 2017). Cloud computing refers the central processing of data and application via internet connection. It provides an online web-based service in a less-costly and efficient way. In terms of benefits for industrial systems, cloud computing enables operational functions such as sharing and co-operation amongst companies (Bellini et al., 2018; Chen & Chiu, 2017; Chen et al., 2018). Augmented reality is used to enhance the figure of physical reality in real-time so added information can support human judgement as well as action. It is one of the cutting-edge technologies for manufacturing, warehousing, logistics and even other business activities e.g. marketing and product design (Netland, 2016; Ruiz-Ruiz et al., 2013). The more trendy and powerful tool of digitalisation is AI due to the booming computing power and data collection. AI technology has significantly improved the efficiency of computer vision, audio recognition, and data analysis, which could help easier achieve automation (Pimenov et al., 2018) and process planning (Jeang, 2015). The other technology which is usually also regarded as AI is robotics. Robotic arms and Automatic Guided Vehicle are core components in smart factory and warehouses. Studies have revealed robotics to be an important enabler for industrial system digitalisation (Daim et al., 2018; Flores-Abad et al., 2014; Villani et al., 2018). Other technologies that are also widely discussed include data mining and big data (Addo-Tenkorang and Helo, 2016; Hazen et al., 2016).

The industrial system digitalisation can also be viewed from different sub-functions. Starting from product design, software including Computer Aided Design, Product Data Management etc. help in the design process. Recently, this list has extended to cloud systems, digital twins (Tao et al. 2019), knowledge management systems (Tiwana and Ramesh, 2001), augmented reality (Arrighi and Mougenot, 2019; Park et al., 2015), 3D printing (Zhang and Yu, 2016) and many others. The sourcing and procurement phase can also be strongly supported by digital technology, including blockchain-supported facility procurement (Gunasekara et al., 2021), and especially the recent e-procurement platform (Bag et al., 2020; Bienhaus and Haddud, 2018; Mishra et al., 2013). Production stage is also transformed with digital technologies such as RFID (Yin et al., 2009), machine learning (Min et al., 2019) and also 3D printing (Kostakis and Papachristou, 2014). Beyond factory-level, there is fruitful amount of studies in logistics and supply chain (Buyukozkan and Gocer, 2018; Seyedghorban et al., 2020).

Going from product to service, digital transformation to industrial system has contributed to servitization (Frank et al., 2019), sharing economy (Davies et al., 2017; Sanasi et al., 2020), and even as a shift of paradigm (Rayna and Striukova 2016).

The adoption and implementation process of different digital technologies is also a topic of researcher's focus. Yang et al. (2021) explored the drivers, process, and impact of digital technology adoption at supply chain level, from both adoption activities and adoption levels. Rodríguez-Espíndola et al. (2022) focuses on risk management related emergent technology adoption processes. Blichfeldt and Faullant (2021) studied the relationship between adoption and product & service innovation. From technological, organizational, and environmental contexts, Ghobakhloo and Ching (2019) discusses the determinants of digital technologies adoption in SMEs. By collecting views of industry leaders, Baslyman (2022) summarized the digital technology implementation process into three main phases: discovery and exploration, planning and assessment, and finally implementation & evaluation.

By reviewing past studies and per our observation, we conclude the following 5 common steps to adopting digital technologies in organizations. Positioning: screening thoroughly at firm and supply chain level to identify bottlenecks and efficiency weak points in the industrial system; Objectives clarifying: clarifying the strategic operation aims of organization, which include cost reducing, quality improvement, fasten delivery, and enhancing flexibility; Scheme selecting: to search for available digital technologies according to organizational strategic aims; Implementing: modify current business processes with the selected digital technology; Finally, performance evaluating: the new industrial system is assessed for functions and performances, and prepared for continuous improvement.

Themes of D1	Literature
Positioning	Discovery and exploration(Baslyman, 2022), Maturity and Resilience of supply Chain (K.E.K. et al., 2022), Risk management (Rauniyar et al., 2022)
Objective Clarifying	Lean (Cifone et al., 2021), Smart manufacturing (Ghobakhloo, 2020), Value-creation (Agrifoglio et al., 2017)
Scheme selecting	Planning and assessment (Baslyman, 2022), Digital Twin (Fuller et al., 2020; Borovkov et al., 2021), Digital manufacturing technologies (Leesakul et al., 2022), Industry 4.0(Kumar et al., 2022), Digital technologies for logistics centre (Parola et al., 2021)
Implementing	Circular economy (Khan et al., 2022), Integrative framework (Margherita et al., 2021), Antecedents and consequences (Gillani et al., 2020), Manufacturing app (Zangiacomi et al., 2017), Service transformation(Ardolino et al., 2018)
Performance evaluating	Implementation and evaluation (Baslyman, 2022), Assessing social acceptability(Kumar et al., 2022), Model closed-loop virtual systems (He et al., 2019), Assessment of enabling technologies (Fuller et al., 2020)

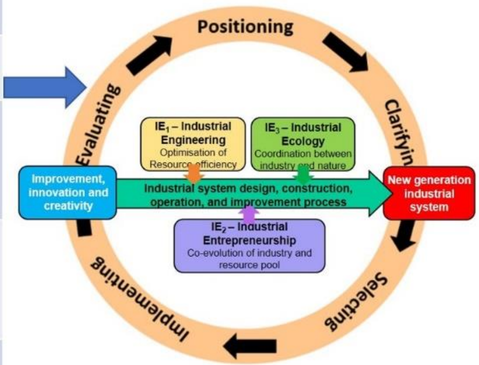

Figure 4. Themes and process of D_1

3.2 D_2: The Industrialisation of Digital Technology

The industrialisation of digital technologies (D_2) is another aspect of digitalisation. Specifically, it explores the paths and process of building new industries around Industrial 4.0 digital technologies, including data asset and analytics, AI and robotics, cloud computing, and IoT. General themes and patterns are to be identified.

Data asset and analytics have delivered countless new application opportunities in business, health care, transportation, and smart city development (Iqbal et al., 2020). In response to technology revolution, resources relating to big data should be secured at organisational level (Comuzzi and Patel, 2016). The industrialisation and rapid adoption of data assets comes from several innovation and novel ideas because there is 1) a decline in data storage cost; 2) growth in the processing speeds of computing devices; 3) breakthroughs of mathematics and algorithms; and 4) development of software platform (Perrons and Jensen, 2015). Big data analytics can be categorised as predictive analytics as it can identify problems forested based on historically collected data, and prescriptive analytics as a strategic tool to enhance firm efficiency and effectiveness by finding solutions (Aydiner et al., 2019). Studies on China's SMEs illustrate that big data analytics can bring both product and process innovation into business operations (Saleem et al., 2020). Big data analytics can also change supply chain performances radically via process design, supplier integration, customer integration (Gunasekaran et al., 2016), and also increase sustainability effects with lean, agile, resilient, and green practices (Raut et al., 2021). Moreover, data asset and analytics can result in completely new business model innovations in various industries (Mayer-Schonberger and Cukier, 2013).

As for AI and robotics industry, globally US and China are competing through product quality, productivity (Arenal et al., 2020), digital business models, and solutions (Woetzel et al., 2017). Using a triple-helix innovation ecosystem framework (Etzkowitz and Leydesdorff, 2000), Arenal et al. (2020) investigated the evolving factors of universities, industries, and government which boost the advancement of AI in China. The government can provide conditions through plans, strategies, regulations, experimentation, along with venture capital, purchases, and access to data support from practical aspects (Arenal et al., 2020). The AI industrialisation and innovation is positively linked with national security, social welfare, and control of cyberspace (Arenal et al., 2020). Universities contribute to AI patents and publications (Arenal et al., 2020). Domestic leading Internet firms deploy the application of AI, while contribute to the training and development of talents together with universities, which significantly accelerates the industrialisation of AI in the areas of security, healthcare, transportation, traffic management in China (Arenal et al., 2020). It is also noted that new policies supporting AI projects can be a trial-and-error approach, and investment opportunities can concentrate in regional or local specialized clusters (Arenal et al., 2020).

Another rapidly growing digital technology is cloud computing, where cloud providers deliver value to users mainly through software as a service, platform as a service and infrastructure as a service (Owens, 2010). Cloud computing is not only a new model of IT delivery and consumption at firm level to reduce cost and improve efficiency, but also a new business model resulting in dynamic changes in industry at a macro level (Marston et al., 2011). This provides opportunities to leapfrog for emerging economies with the rise of new players (Urstsky, 2014), challenging the traditional IT vendors and incumbents (Cusumano, 2010; Yu et al., 2016). Based on an in-depth study on China's cloud computing industry, three phases are identified as the evolution and industrialisation process, namely initiating the concept, building cloud infrastructure, and developing cloud ecosystem (Yu et al., 2016). The central government plays a vital role through planning and controlling in the early stages, while multinational enterprises exploit the emerging market (Yu et al., 2016). In the second stage, local government and telecommunication operations work together on infrastructure building for cloud computing services (Yu et al., 2016). Companies expand the existing business network to adopt first-mover advantage (Yu et al., 2016). In the third stage, SMEs, more domestic IT vendors, and cloud clients play an active role, while central government nurtures domestic players and ensures information security (Yu et al., 2016). Along with the evolution towards cloud computing industry ecosystem, the government-business partnership upgrades from the project-level to system-level with shared vision (Yu et al., 2016).

The phenomenon of ecosystem is also observed in the IoT sector, where synergy can be achieved not only through the skills in complementor, production, and process connection, but also via suitable forms of communication, coordination, and trust between business parties involved (Saarikko, et al., 2017). Due to the characteristics of adaptability, flexibility, scalability, transparency, and traceability, IoT technologies has been adopted to improve operational process, create value, and reduce cost (Chui et al., 2010). It represents a paradigm of innovation that creates value: increasing intellectual capital value and economic value of companies (Murray et al., 2016). Through monitoring real-time remanufacturing, IoT can contribute to greener production and sustainability (Zhang et al., 2018). IoT technologies are not only applied to supply chains or industrial systems, but also connect actors such as government and IP organisations, which enables cross-industry collaboration (Rong et al., 2015). Based on the interaction among focal firms and customers in the context of business ecosystems, the IoT industry demonstrate three patterns: 1) high-open IoT ecosystem, where customers and stakeholders can obtain and use data to assist the focal firm for co-creation; 2) medium-open IoT ecosystem, where customers use and change products; 3) less-open ecosystem, where the focal firm controls the product development with customer feedback (Rong et al., 2015). The degree of ecosystem openness reflects the lifecycle of IoT industry, with high-open pattern at emerging stage, medium-open pattern at less mature stage, and less-open pattern at industry mature stage (Rong, et al., 2015).

Key themes from the current literature related to the industrialisation of digital technologies (D_2) can be summarised in Figure 5 with 5 common steps. Collecting experiences: collecting successful digital technology development and application experiences alongside innovation and creative idea; Generalising the model: through re-design and development of the experiences; Building up the industry: defining products and services as well as their industrial systems in regard to specific industry sectors; Operating and improving: operating and continuously improving the industrial systems to deliver the products and services; Embedding and iterating: embedding the industrial system within its communities or ecosystem on a continuous base.

Themes of D2	Literature
Collecting experiences (Creativity nurture)	Application opportunities (Iqbal et al., 2020; Arenal et al., 2020), New areas (Iqbal et al., 2020), Innovation/novel ideas (Perrons and Jensen, 2015); Initiating concept (Yu et al., 2016)
Generalising the model (Design & development)	Process design (Gunasekaran et al., 2016), Value creation (Murray et al., 2016), New business model (May-Schonberger and Cuker, 2013; Woetzel et al., 2017, Marston et al., 20211), Solutions (Aydiner et al., 2019), Product and process innovation (Saleem et al., 2020), New service (Owens, 2010)
Building up the industry	Building infrastructure (Yu et al., 2016), Specialised Cluster (Arenal et al., 2020), Supplier integration (Gunasekaran et al., 2016), Government support (Arena et al., 2020)
Operating and improving	Business operations (Saleem et al., 2020); Performance improvement (Raut et al., 2021), Trial and error (Arenal et al., 2020), Process improvement (Chui et al., 2010), Increased effect (Raut et al., 2021)
Embedding and iterating	Triple-helix innovation ecosystem (Arenal et al., 2020), Developing ecosystem (Yu et al., 2016), System-level with shared vision (Yu et al., 2016), Co-creation (Rong et al., 2015), Cross-industry collaboration (Rong et al, 2015), Business network (Yu et al., 2016)

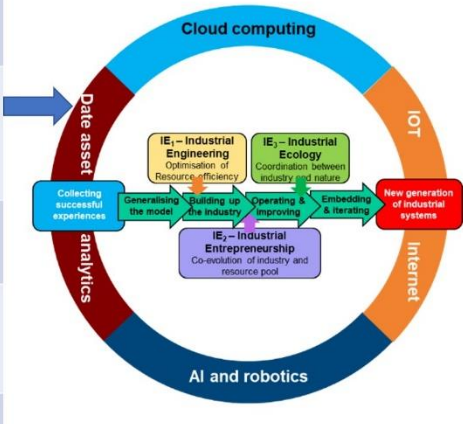

Figure 5. Themes and process of D_2

4. An Integrative IED Framework

Based on the literature review, this section seeks to develop an integrated model demonstrating not only the traditional industrialisation process for value creation but also the interactions between the ecologicalisation and digitalisation processes. Because of their complex relationships, the section starts with an industry case study illustrating the D_1 and D_2 interactions, and then conceptually link them with the established IE^3 model in order to provide an integrated IED Framework.

4.1 Inspirations from Industry – Alicloud Development

It is clear from the literature reviews that industrialisation is the foundation whereas ecologicalisation is a strong constraint and that digital technologies applied in industrial system are quite fragmented. The following case demonstrates a Chinese e-commerce company's transformation journey and implies that industrialisation can sometimes require support from new technology (digitalisation, D_1) and that new technology applications can trigger new business emergence by expanding the core technology in other related industries.

Established in 1999 in Hangzhou, Alibaba Group has a wide range of businesses including Taobao.com, Tmall, AliExpress, Alicloud, Cainiao Logistics, 1688, Alimama, Xunxi, Alibaba DAMO Academy. As one of the ICT giants nationwide, Alibaba contributes significantly to the developments not only in Zhejiang Province but also for the new economy of the world. In 2019, Alibaba Group had an annual sales volume of £37.6 billion and 103,699 employees. However, the company was never a guaranteed success from the very beginning and understanding its developmental path is meaningful and inspirational. Alicloud, one of the core business units in Alibaba Group, had its dramatic growth journey illustrating the business digitalization (D_1) and digital technology industrialization (D_2), as well as the challenges during the journey.

Every year after 2008, during the annual Singles' Day festival which is China's largest online shopping seasons, Alibaba as the No.1 online shopping platform always faces enormous challenge on system computation capacity to support the peak time of transactions. For example, at 11 pm of the 11th November 2020, the Alibaba payment tool Alipay had recorded 2.25 billion transactions with a spike of 583,000 in the first 26th second[1]. The very successful marketing event asked business operations to provide compatible and reliable physical capacity to support.

In order to provide such high-capacity demand, Alibaba had to develop its cloud-computing infrastructure and relevant human & technical resources. But to develop and sustain the complex cloud system requires a high price and can be wasteful considering the online transaction numbers of Alipay are much lower during normal times. A mechanism of better utilization to the redundant cloud-computing capacity is needed for Alibaba's mega system.

Alibaba then forged its internal cloud computing into a stand-alone business unit which provided cloud-computing service to external companies, particularly to SMEs. The cloud service can utilize Alibaba's spare capacity to generate a new revenue stream. And soon Alibaba realized that it is more than just a business and is a potentially industry to enable a "cloud platform" to support SME's operations, e.g. accounting, customer service, logistics, and payments.

In order to nurture the Alicloud business, besides providing the cloud service to SMEs, Alibaba also cooperated with Hangzhou Municipal government on digital projects including smart city and transportation using its cloud service platform. The diversified collaborations provided not only enough development funding but also trained the platform to face very different requirements and industrial demands.

Alicloud platform had developed a successful process in design, construction and operation with less hurdles. One reason for this success is attributed to Alibaba's previous experience in E-commerce and accumulated technical capability in Information Technology and Data processing. However, it is not easy to transfer this technical capability and apply it in new industries.

To overcome these hurdles in cross-industry transfer, Alibaba chose the firms in the manufacturing sector which is just upstream of E-commerce platforms. The female garment industry was chosen for a pilot. Alibaba leveraged the IoT and AI as the backbone technologies for its smart manufacturing platform 'Xiniu (Rhino) Manufacturing'. The Xiniu smart manufacturing links the customer demands directly with the upstream apparel manufacturer, enabling low stocking, short processing time and minimum order amount. This technological solution balanced both the production flexibility and time/material efficiency.

After the nearly five years of preparation, Alibaba advertise this Xiniu smart manufacturing business unit publicly at 2020, but there has been little in progress updates about it in the last two years. This can highlight that applying key ICT technologies in an attempt to digitalize traditional industries is not easy. More in-depth consideration into industry-specific knowledge and patterns are needed.

The Alicloud business evolution case stimulates the future of industrialisation, as shown in the IE^3 framework (Figure 3), in regard to new technologies in the industrial system. Additionally, the applications of the new technology like digitalisation (D_1) will also create more industrial crises including challenges and potentials. The crises will encourage industrial companies to tackle the challenges and utilise the potential, like Alicloud. Therefore, a more integrated framework should be developed to capture opportunities more comprehensively during industrialisation.

4.2 Building up an integrated research framework

Based on our research question of "How to integrate IED for sustainable development", we seek to synthesise the previously discussed perspectives of industrial system ecologicalisation (IE^3 in Figure 3) and the two types of digitalised industrial developments (D_1 in Figure 4 and D_2 in Figure 5) to ultimately propose an integrated theoretical framework as Figure 6.

Figure 6 consists of three main parts that demonstrate the integration process. The large circle on the right side of Figure 6 is the integrated framework for IED and the arrows demonstrate where the three separate models (IE^3, D_1 and D_2) that were previously discussed in this paper come from. The IED framework inherits directly from the IE^3 model in order to focus on the value creation process from innovation within the industrial system while considering resource constraints & outcome and environmental impact issues. Meanwhile, for digital contexts, the two driving forces of D_1 & D_2, located at the top and bottom respectively, not only trigger wide applications of digital technology in industrial systems but also inspire digital applications to be industrialised. Through integration, the IED framework fundamentally provides a process-oriented tool demonstrating industrialisation with sustainability and digital technological supports.

When considering the integrated framework, the right part of the Figure 6, the key component is still the industrialisation process based on innovation towards new generation of industrial systems, and fundamentally supported by the two digitalisation circles. The IE^3 three function modules (IE_1, IE_2 and IE_3) still constrain and redefine the industrialisation process in order to ensure the new generation of industrialisation and its industrial systems can satisfy not only quick response to the customer and competitor requirements but also the environmental requirements. The dual circles of digitalisations (D_1 and D_2) lay down a new foundation for industrialisation – the inner circle (D_1) applies digital technologies in the established industrial systems to enhance the systems' competitive advantages while the outer circle (D_2) collects D_1 successful practices and experiences to formalise and industrialise them into new types of systems.

In summary, the integrated IED framework inherits IE^3 core functions – industrialisation with business and environmental ecosystem considerations – and takes advantage of the digital technologies in the both ways. It demonstrates an iterative learning process between IED.

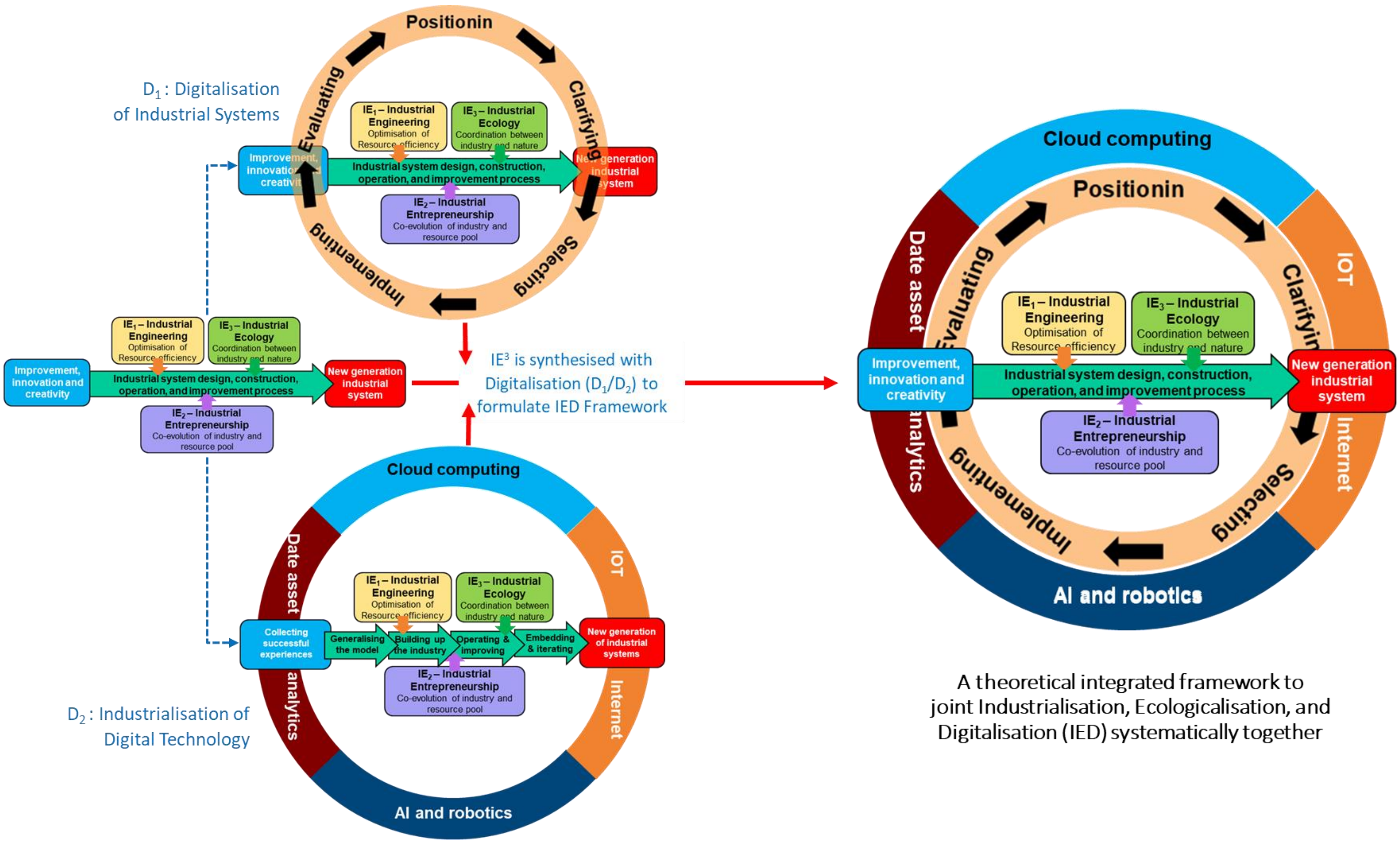

Figure 6. A theoretical framework to integrate IED

4.3 Discussion from theoretical and practical perspectives

The IED framework (Figure 6) covers multiple subject areas with great interactive relationships. It is sensible to explore its properties and potentials for both the academic and practical worlds. There are three specific questions for further discussion, from theory and practice aspects.

Discussion question 1: *"Why bother – why do we need to have this complex framework?"* A holistic and systematic view on the situation is required due to the complexity of the world. Because of limited knowledge, the Chinese government and its people used to believe that iron-steel was the most crucial aspect in the national industrialisation in the 1950s and GDP was the most important in the modernisation ten years ago; stupid and serious mistakes were made. The root-cause of the mistakes can be traces to the lack of comprehensive understandings about industrial, economical, and societal developments – their interactive and complex relationship. If there was a comprehensive and systematic picture, it could extend visions from a single-minded approach and small area towards a much wider and interactive areas. The same principle can be found in the interactive relationships between IED, which needs to become better understood and balanced. Regarding the complexity, the systematic structure arrangement can improve its rationality through the functional module and strategic architectural design.

Discussion question 2: *"What can an academic research framework offer in a theoretical development?"* Seeking to integrate three different objectives of IED. The framework shown in Figure 6 includes three layers of the sub-systems but eventually anchors on the top layer – industrialisation – where industrial system development is supported by new environmentally friendly and digital technologies. The theoretical framework should be scientifically verifiable via individual module development and framework iterative improvement. The paper attempts to explore a generic protocol to develop a conceptual framework to cope with increasingly difficult emerging challenges.

Discussion question 3: *"From a practical perspective, will the framework benefit industrialists and policy makers?"* The framework provides a systematic structure to ensure the modules compatible with the strategic aims at the framework level. Each functional module also breaks down the detailed objectives and provides compatible theoretical knowledge and practical tools. The framework integrates required knowledge and technologies in order to form a new body of knowledge dedicated to new industrial issues. The framework can be deconstructed into specific practical tools and solution-oriented knowledge and experiences.

In summary, although the integrated framework (the right part of the Figure 6) looks quite complex, it can be better understood easily from two levels. The first level is its strategic function modules; it constitutes of three basic modules – IE3, D1 and D2 that seek to achieve industrialisation by considering two more variables – ecologicalisation for sustainability and digitalisation for more advanced technology applications in industrial systems. The left part of the Figure 6 demonstrates the three function modules. The second level is the detailed individual processes within the function modules. The detailed processes can not be seen in the Figure 6, but can be traced back to each module process, illustrated in Figure 2, 4 and 5. The existing integrated framework has not specifically demonstrated and tackled the interactions between the modules, which give the future research more imaginable space and exciting clues.

5. Future research agenda and conclusion

5.1 Research Agenda and Design

Based on the proposed IED framework, future research follows the Pragmatist research paradigm that aims to provide practical solutions for problems to help future practice (Visser, 2019) as it intends to resolve the many challenges such as the VUCA circumstances, resilience, sustainability, etc. that the industry is currently facing. The research will take a deductive approach which starts with an incomplete observation (IED framework in Figure 6) before undertaking the task of explaining it, encompassing the whole process from data to conclusion (Reichertz, 2001; Bryman and Bell, 2015).

The research methodology will attempt to be as practical as possible in guiding the research while being conscious of real-life circumstances; it will take inspiration from the Design Research Methodology (DRM) and Process-oriented methodology (Figure 7).

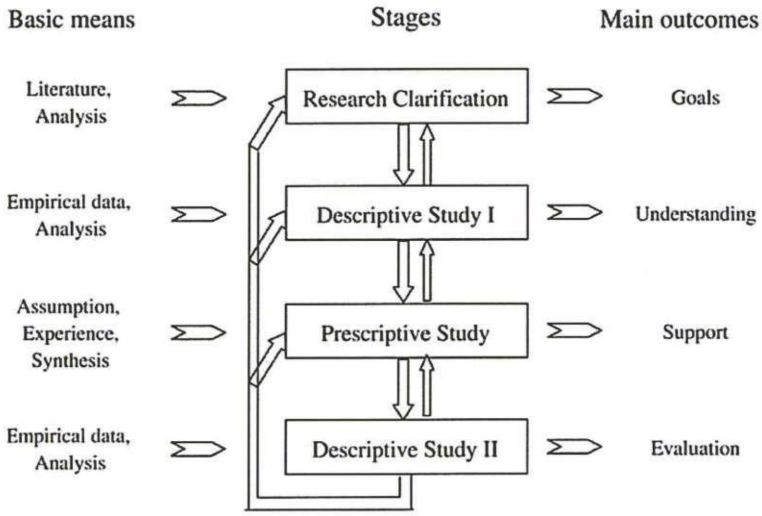

Figure 7. DRM framework
Source: Blessing and Chakrabarti, 2009

Figure 7 shows an iterative process that usually consists of a research clarification stage, at least two descriptive studies, and at least one prescriptive study in between the descriptive studies and their goals. An important note is that there are two-way connections between the stages, showing that it is possible to progress the research in a multitude of ways and allow for as many iterations of the process depending on how in-depth the research desires to delve into the topic. This process allows for the findings to be scrutinised with academic research in a fluid manner to study the subject in great detail and reach a realistic evaluation.

Process-oriented methodology is similar as it is defined by developing a process that is firmly rooted in existing theory and followed by testing and refining through real-life applications (Platts, 1993). The similarity between the two is the initial stage of research clarification and the testing and re-evaluation of the research like the descriptive and prescriptive studies. The difference between them is that Process-oriented methodology has a specific flow in its testing and re-evaluation process where it starts with a small number of organisations, then followed with the testing of the process for wider applicability after potential revisions from initial testing (Platts, 1994).

The key components that are utilised is the iterative process, between empirical data & analysis and the reflection of that data. The iterative cycle when applied to this research means evaluating the framework via gathering & analysing empirical data and improving the framework by integrating & reviewing all the information together, until it reaches saturation where nothing new is gained. This process can further highlight new ideas and demands which will help ensure a high effectiveness for the framework while also enriching and building on the body of knowledge.

The framework and its various modules will be investigated as shown in Table 1. Each research module is split into its respective research module objectives, tasks associated, research approach, and research process/stage classification; this has been done to ensure clarity and conciseness. The research approach will vary as the subject of the research objective changes and at which stage the research is in. In general surveys will gather data for a holistic view, case observations will find best practices, interviews will enrich and investigate the subject at greater length and depth, and experimentation will act to explore the possibilities of new ideas or concepts.

Table 1. IED research modules and relevant research approaches

<table>
<tr><th colspan="2">Research Design / Research Module</th><th>Research Module Objectives</th><th>Main Research Module Tasks</th><th>Key Research Approaches</th><th>Main Research Process/Stages</th></tr>
<tr><td colspan="2">IE_1 Module – Industrial Eng.</td><td>Value-based Resource Efficiency</td><td>• Resource cascading
• nRs (Re-…)</td><td>Case observation to capture the best practices and prescription</td><td>• Industry & literature review for selecting cases
• Data collection/ analysis of current practices</td></tr>
<tr><td colspan="2">IE_2 Module – Innovative Entrepreneurship</td><td>Design-construct industrial system from R Pool</td><td>• Innovation
• Business models</td><td>Interviews with current leaders within industry to identify current business models and innovation efforts</td><td>Data collection/ analysis of existing systems and reflecting upon it</td></tr>
<tr><td colspan="2">IE_3 Module – Industrial Symbiosis for New Value Creation</td><td>Waste and by-product utilisation through industrialisation</td><td>• Resource efficiency
• Supply chain/ network</td><td>Case observation to understand processes and implementation</td><td>• Industry & literature review for selecting cases
• Data collection/ analysis of recent methods</td></tr>
<tr><td colspan="2">D_1 Module – Industrial System Digitalisation</td><td>Upgrading existing industrial system through digitalisation</td><td>• Lifecycle analysis & assessments
• Smart manufacturing</td><td>• Interviews with existing experts on the topic
• Experimentation of theoretical ideas in this new field</td><td>• Hypothesising the implementation of the system and its impacts
• Data collection on its practical implications</td></tr>
<tr><td colspan="2">D_2 Module – Digital Technology Industrialisation</td><td>Identification of some digital technologies and transformation of them towards new industries</td><td>Cloud based programming Platforms for increased flexibility & adaptability</td><td>Surveys to obtain data on the many different types of cloud computing & platforms in relation to industry</td><td>Data collection on the different digital tools and their individual/ collection impact on industry</td></tr>
<tr><td rowspan="4">Synthesising Modules</td><td>Resource cascading platform</td><td>Digital platform dedicated to the IE_1 Module in order to provide relevant data and tool bases</td><td>• Allocation of resources in the ecosystem
• Optimising use of all materials (raw & waste)</td><td>Interviews with individuals with know-how on database/ platform creation</td><td>Data analysis of the process and difficulties in creating a resource cascading system</td></tr>
<tr><td>Social resource development platform</td><td>Digital platform dedicated to the IE_2 Module in order to provide relevant data and tool bases</td><td>• Nurturing business ecosystems
• System stability</td><td>Interviews with industry leaders/ municipalities/ government</td><td>Data collection on how to best create a stable & nurturing environment for the industry</td></tr>
<tr><td>Waste/by-product symbiosis platform</td><td>Digital platform dedicated to the IE_3 Module in order to provide relevant data and tool bases</td><td>• Identification of links via waste/ by-products
• Managing complex supply chain/networks</td><td>• Surveys to obtain information on what types of waste/by-products exist
• Focus groups with companies in the industry</td><td>Data collection/analysis on the types of waste/by-products and their potential links</td></tr>
<tr><td>Open module for the emerging requirements</td><td>Digital platform for emerging issue and requirement in order to provide relevant data and tool base supports</td><td>Open innovation
Investigation into the potential of new digital platforms</td><td>Surveys to capture data regarding emerging issues and new breakthroughs in technology</td><td>Identification of new ideas and requirements for the research/ framework</td></tr>
</table>

5.2 Theory and practice implication

To overcome the current challenges and transform towards a sustainability oriented industrial system, an integration of IED in the manufacturing sectors is required. While extant literature covers the concepts separately, our paper provides a holistic view. First, we have critically reviewed and interpreted the current literature of IED in terms of ecologicalised industrialisation (IE^3), industrial system digitalisation (D_1), industrialisation of digital technology (D_2). Key themes are identified, which can capture the emerging trends of those theories with critical interpretation. Second, we have proposed a theoretical framework (Figure 6) combining IED, highlighting the modules, integration architecture, mechanism, and dynamic paths. Third, we have designed a process orientated abductive methodology to validate the framework. The core modules and interaction mechanism are pointed out alongside research objectives, design, and methods. With the research design shown in Table 1, scholars from various backgrounds can conduct research projects with tailored local needs. Thus, our findings can be a platform to enrich the theory together.

As for practical implication, organisations can use the framework to rethink & redesign their business model, combine business growth & sustainability in a proactive way, and add value in the long-term. They can follow a step by step process accordingly to build up the various modules addressed in the framework. In times of crisis e.g. Covid-19 pandemic, facing with demand uncertainty and other complex factors, they can use it to reconfigure the resources with digital transformation. The understanding of the IED synergy model along with the interaction mechanisms can help organisations to become change-oriented and better manage unpredictability. In a boarder context, policy makers can also refer to our framework to support circular economy and digitalisation with value capture and creation. Specifically, for developing countries where most manufacturing systems take place, the priority is to achieve industrialisation. However, they need to make sure that the industrialisation journey is sustainable, factoring in environmentally friendly process design and support systems. Meanwhile, digitalisation can support both industrialisation and ecologicalisation processes. As for developed countries which have already achieved industrialisation but are facing upgrading and transformation challenges, the focus can be environmental protection, because this is the basic requirement for external survival. Although digitalisation will affect competitiveness on both firm and nation levels, the purpose of digitalisation is still fundamentally to provide service and support for industrialisation and environmental protection.

In conclusion, this paper provides critical reflection on existing literature on IED and includes a theoretical framework and new research methodology which demonstrate significant theory and practical contribution. Through this paper, we also hope to communicate with scholars from various backgrounds as we look for opportunities for future research collaboration on IED. The research objectives, tasks, approaches, and processes of each module are identified in Table 1. To conduct the research, priorities can be given according to industry requirement or theory gaps. For one thing, the research will adopt a deductive approach, involving the verification, improvement and enrichment of the modules as an iterative process. This can begin with the exploration of industry need and opportunities, and then the verification. Alternatively, studies can follow the knowledge maturity levels. A lower level of knowledge maturity means to identify why the IED system and sub-systems (e.g. modules) are needed. This is followed by the description of the systems, e.g. what are the key elements. A higher level of knowledge maturity focuses on how to design and improve the system, that is, to develop process-oriented knowledge. Thus, based on this agenda and module characteristics, in order to improve and verify the module through the iterations, the prioritised areas to start with can be D_1 Module – Industrial System Digitalisation, and D_2 Module – Digital Technology Industrialisation. Compared to the established bodies of knowledge in terms of industrial engineering, D_1 and D_2 are emerging topics, demonstrating more research gaps. Particularly, the D1 & D2 interaction with IE3-Industrial Ecology or say sustainability demand is in more urgent need for research development. There are further two dimensions for exploration: the first dimension to further research into the sustainability impact of D2, considering that large-scale deployment of data centre and relevant applications are consuming significant amount of energy; the second fold is to examine how does D1 -- digital technology can serve the purpose to improve industrial system's sustainability performance, in regards to environmental footprint measurement, energy & resources efficiency, social impact etc.

In additional to the topics in Table 1, other future research include: What are the relationships among the different modules? As the framework is still open, are there any new themes or modules, which can be added to the framework along with the abductive research? What is the cascading strategy, and how can it be linked to industrial symbiosis? How can the online database serve circular economy and industrial symbiosis? How can AI, data asset and analytics, and other digital technology help to optimise the use of raw material, with the design and development of a complex adaptive industrial system?

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