Sustainability Alignment of Supplier during Industrial Revolutions

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Suppliers have evolved alongside industrial revolutions, induced by their selection criteria for over two centuries. They have marched in step from mechanization (Industry 1.0) to mass production (Industry 2.0), customization (Industry 3.0), and digitalization (Industry 4.0 and 5.0). They have grown from standalone competitors to supply chains as their selectivity has escalated from a single measure to multiple criteria. Meanwhile, sustainability has remained a pledge with no enforceable indicators in their inter-creditor agreement, leading to a lack of social responsibility and ecological accountability.

supplier selection criteria | environmental sustainability | economic sustainability

1. Industry 1.0

The first industrial revolution was celebrated in the mid-18th century in England in a society depending on agrarian and artisan production [1]. The characteristics of this revolution were a transition to the use of steam-powered engines, benefiting the textile and transportation industries, which led to the construction of factories, increased urbanization, and labor mobility. By the end of the 18th century, accelerated mechanization had increased productivity with low product variety in a high-demand market spreading throughout the UK and Europe [2]. In 1869, the first transcontinental railroad in the US was built, followed by Samuel Morse creating the telegraph, Andrew Carnegie building the first steel mills, and Alexander Graham Bell inventing the telephone [3]. Coal became the main energy source for manufacturing processes and transportation [4] as ashes contaminated the environment, and the atmospheric CO_2 rose from 280 ppm. Meanwhile, suppliers navigated alongside the revolutionists as independent and fragmented entities from the mid-1750s to the early 1860s. While supplier selection was regarded as the most important function, selectivity was based on the net unit price based on three indicators: price, freight charges, and ordering costs. There was no sign of social responsibility and environmental accountability for industrialists, as presented in **Figure 1**.

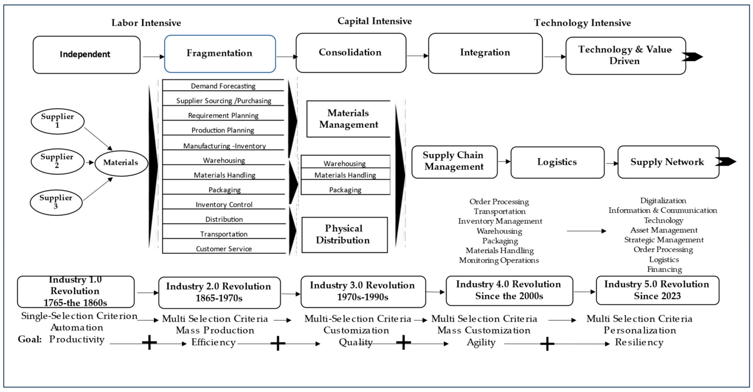

Figure 1. Suppliers' evolution alongside industrial revolutions and their selection criteria [5].

2. Industry 2.0

Industry 2.0 emerged from the ashes and CO_2 of Industry 1.0 in the late 18th century, illuminated by electricity to pave the path to the Fordist paradigm in the 19th century in Germany, America, and the UK. The revolution penetrated other regions and altered commerce by integrating science and new technologies that featured productivity, specialized workers, and well-planned manufacturing processes. Streamlined mass production was based on volume, variety, and the principle of scientific management, with which Henry Ford (1863–1947) and Frederick Taylor (1856–1915) were linked. The discovery of oil also marked this era. Thus, transportation extended from land and water to air as cars, buses, planes, and ships became the means of conveyance. Materials such as metals, synthetic materials such as plastic and nylon derived from the oil industry, and dyes spawned inventions, transforming the communication system with the associated advances in chemistry and metallurgy [1].

The growing production of steel, iron, coal, oil, chemical, and agricultural fertilizer supplies met the demands of industries such as automobiles, textiles, agriculture, and the construction of transportation infrastructure. The inventions of the combustion engine, semi-trucks, forklifts, equipment for handling materials, pallets, and rudimentary equipment led to efficient fragmented suppliers [6]. This era saw industrial engineering and operations research consolidation in purchasing processes. Suppliers' selection requirements increased from net unit price to productivity and production capacity [7].

Supply sourcing was selected based on multi-selection criteria, while the related activities (purchasing, warehousing, and logistics) were fragmented. The indicators for supply selection were the unit net price considering the associated costs (ordering and transportation), productivity, and quantity. The sources of energy were coal, wood, and electricity, and the immediate roots of greenhouse gas emissions were established between the late 1950s and the early 1980s (**Figure 1**).

3. Industry 3.0

The third industrial revolution emerged in the early 1980s, marked by the rise of electronics and the innovation of technology from analog to digital. Automated systems replaced mechanical ones in mass production, with the ability to carry out complicated human tasks. Industries began to use computers, information technology (IT), and electronics in many production processes, thus engendering memory-programmable logic controller robots, flexible manufacturing [8], computer-integrated manufacturing [9], computer-aided design [10], and lean manufacturing as an extension of just-in-time manufacturing. In the 1990s, with the transition to digitalization and the internet, the term “metaverse” was coined to denote a three-dimensional space within which people and physical objects could interact and share information [11]. This transition paved the path to a virtual environment with numerous advantages, such as productivity, efficiency, and flexibility. Electronic devices and software systems facilitated supply activities such as inventory management, tracking products, planning the resources of enterprises, scheduling product flows, and shipping logistics. The third supplier's evolution occurred in two phases. Phase one was between the 1930s and 1950s, as functional activities consolidated into two branches: (a) the management of materials associated with producing parts and finished goods, including their packaging, and (b) physical distribution, which involved making parts and finished goods available for consumption, transportation, and warehousing [7].

The competitive advantage of oil imports over domestic coal initiated a new energy source with low prices, easier material handling, and lower environmental pollution. By 1980, the share of coal had dropped to 22% while that of oil had risen to 60%. Yet, environmental contamination in this period is considered the transition to the rapid loss of global sustainability.

Consolidated suppliers were evaluated based on multi-selection criteria, customization, and quality. In 1982, Oliver and Webber coined the term “supply chain management,” defined as the sequence of activities from the procurement of raw materials to their transformation into finished goods, packaging, and distribution to customers. It involves planning, implementing, and controlling the interconnected supply operations to meet customers' requirements. The supply chain incorporates facilities that transform raw materials into intermediate/final products and deliver them to customers through a distribution system to the users. It bridges procurement, manufacturing, and distribution [12]. During this evolution, several hardware and software providers supported supply chain management in communication, optimization, and modeling, such as i2 Technologies, SAP, Oracle, and Invensys [13].

During this period, supply evolution highlighted the integration of purchasing activities with logistics, acting as a fundamental connection emphasizing the upstream and downstream flow of materials, with the reorder point based on the available inventory and associated costs. The distribution of materials shifted from railroad to intermodal, air, and maritime transportation with containerization in 1990. This reduced logistics and transportation costs while creating an infrastructure for global supply chains supported by IBM's first computerized inventory management and forecasting system in 1967. This system streamlined logistics and created opportunities in inventory management and warehousing [14]. Enterprise resource planning systems and radio frequency identification (RFID) tags helped to manage goods and shipments electronically [15].

In 2000, supply chain networks introduced a framework for value chains with five criteria, including (1) an input–output structure (i.e., a set of products and services connected in a sequence of value-adding economic activities), (2) territoriality (i.e., the spatial dispersion or concentration of production and marketing networks comprising enterprises of different sizes and types), (3) a governance structure (i.e., the authority and power relationships that determine how financial, material, and human resources are allocated and flow within a chain), (4) the manufacturing/technology governing producer-driven chains, and (5) the buyer-driven chains of the commercial and service sector [7][16][17].

During the third industrial revolution, suppliers' selection criteria extended from net price and productivity to performance and warranty policies, with 23 indicators [18], with order processing, forecasting, warehousing, packaging, scheduling, and transportation added later. Other supplier selection criteria were quality (percentage of rework and percentage of returned items), reliability (supplies availability from certified/reputable third-party suppliers), service responsiveness (after-sale dependability and return policy), financial stability (revenue, profit, financial assets, and credit ratio), location capacity (geographical location and capacity of distribution centers), and consistency (in terms of price, quantity, quality, delivery, liability, and responsiveness/just-in-time purchasing). Additionally, suppliers' selection criteria for transitioning from analog to digital required software, such as flexible spreadsheets, mapping, and route planning, which tracked costs and schedules [5][19][20] (**Figure 1**). There were still no signs of sustainability requirements, and the price to pay for these advancements was the gradual destruction of the environment because these advancements relied on fossil fuels such as coal, natural gas, and petroleum.

4. Industry 4.0

The Industry 4.0 revolution outshone its predecessors with digitalization and the convergence of breakthrough technologies (such as advanced robotics, artificial intelligence, the Internet of Things, virtual and augmented reality, wearables, and additive manufacturing). It was introduced as a three-dimensional architecture at the 2011 Hannover Fair in Germany. This industry encompasses the products' lifecycle, business layers, and factory hierarchy by converging digital and physical control through intelligent network systems capable of exchanging information and controlling operations autonomously [21][22][23]. Physical technologies include smart assets, 3D/additive manufacturing, cyber–physical systems, uncrewed aerial vehicles (drones), autonomous robots, virtual and augmented reality, radio frequency identification, sensors and actuators, advanced materials, and nanotechnology in horizontally and vertically integrated systems [24]. These technologies and predictive/prescriptive analyses allow more accurate and reliable decision making for quality and efficiency.

Supply chains supporting Industrial Revolution 4.0 leverage embedded intelligence in their processes, enabled by artificial intelligence [25], machine learning as a subset of artificial intelligence (AI) [26], virtual and augmented reality, big data and analytics, cloud computing, cloud manufacturing, cybersecurity, automation, robotics, the Internet of Things, cyber–physical systems, and additive manufacturing (3D, 4D, and 5D printing) [27].

This evolution emphasizes integrating communication and smart information technologies with the mass utilization of network connections that incorporate automation and computer technologies to increase transparency and optimize time, cost, materials, people, and equipment [28]. According to Frederico et al. [29], this evolution is a holistic approach utilizing advanced technologies to streamline operational processes. The goals are product customization and personalization by allowing for automated data ingestion and contextualization to predict and understand customers' preferences while harnessing artificial intelligence, deep learning, and data analytics.

Supply chains of Industry 4.0 are at the center of the digital enterprise encompassing the complexity of lateral links, reverse loops, and two-way exchanges that require a broad, strategic view of resource acquisition, development, management, and transformation. They comprise the general state of business affairs in which integrated planning and execution, logistics, procurement, warehousing, data analysis, and materials (i.e., work-in-process and finished goods) are transformed and moved through a value chain (**Figure 1**).

The predominant selection criteria for the fourth supply chain revolution are efficiency, responsiveness, flexibility, agility, transparency, safety, compliance, and special customer relationships. Valeske et al. and Lee and Seshia [21][24] believe that the suppliers' selection criteria in Industry 4.0 are founded on the previous criteria with the addition of technical capabilities (real-time monitoring, control, lifecycle management, service-based interaction, advanced analytics, autonomous collaboration, security, and trust), engineering (model-based methods, safe programming, validation, resilience, risk mitigation, tools for lifecycle support, advanced operating systems and programming languages, and simulations), infrastructure (multi-domain interoperability, migration, compatibility with legacy systems, integration, resilience, robustness, and the sustainability of critical infrastructure), human-centric and updated ecosystems (education/training, collaborative intelligence, a cross-industry knowledge base, benchmarked practices, and emergent behavior), and information systems (artificial intelligence (AI), the industrial Internet of Things (IoT), cross-domain large-scale information management, the transformation of data and information analytics into actionable knowledge, automated knowledge-driven decision making, management, risk analysis, and autonomous smart systems within an ambient intelligence ecosystem).

The environmental sustainability of Industry 4.0 and the percentage of CO_2 emissions depends on the mode of transport (road accounting for 57%, ocean freight 17%, air freight 9%, and rail freight 6%). The technologies associated with the fourth industrial revolution can cause significant ecological damage due to generating electronic waste.

5. Industry 5.0

Industry 5.0 is built on the technological platforms of Industry 4.0, shifting the focus from being technology-driven to being value-driven, moving away from social welfare to social well-being [30]. This revolution reflects a vision beyond productivity and efficiency, sustainability, and resiliency, reinforcing industries' contributions to society concerning the Earth's limited resources. Targeting mass customization, the foundation of Industry 5.0 is based on three pillars: intelligent devices, intelligent systems, and intelligent automation/autonomous robots, all fully merged with the physical world in cooperation with human intelligence for flawless production and minimum waste. It utilizes six enabling technologies: (1) collaborative robots (cobots) as human–machine interaction technologies that interconnect and combine the strengths of humans and machines, bio-inspired technologies, and smart materials that allow materials to be embedded with smart sensors and enhanced features while being recyclable; (2) digital twins and simulations to model entire systems; (3) the internet of everything and the artificial intelligence of things, blockchain, edge and fog computing, cognitive computing, 6G, and beyond; (4) augmented reality; (5) mixed reality; and (6) holography [27].

Industry 5.0 disrupts supply chains and the related networks in their infancy because the transactions are managed within the platform and governed by blockchain [31]. Therefore, intermediaries within the supply chain disappear. Additionally, new relationships, such as those between the companies that own the platforms, technology designers, and internet servers, change the structure of the supply chains [32], requiring visibility, transparency, and trust by all participants [33]. These features allow supply chain leaders to evaluate the suppliers' green attitudes and thus select only truly green suppliers to be included in the supply chain network.

A serious challenge is that modern technologies, such as using blockchain to manage transactions, require skills and competencies for efficient transactions. This can be extended only to regions and countries where the available infrastructure supports technology, augmenting territorial discrimination and disparities [34][35].

Thus, the criteria of a supply chain extend to digital capabilities, hyper-connectivity, the integration of intelligence and cognitive computing, being human-centric, and resilience (**Figure 1**). As such, suppliers' technological capabilities have to extend to cyber–physical systems connecting the worlds of humans, machines, information, and organizations for integrated operation, an approach driven by adopting new disruptive technologies for flexibility in the face of changing requirements. For example, digital twins are used for simulation and testing before implementation to ensure products' precision and faster execution without bottlenecks. Asset performance management is used for real-time diagnoses of plants and equipment to predict and plan convenient maintenance schedules and eliminate unplanned shutdowns. Lifecycle product management integrates and simulates the compatibility of all components of a new product in real time and is used to plan for a successful launch. Industrial IoT-driven total automation integrates the management of the plant, logistics, and supply chain. Human/machine collaboration involves collaborative robots to enable better precision, faster execution, the personification of products, and the minimization of waste. Digital transformation enables a connected process linking the plant, the supply chain, OEMs, customers, and all other stakeholders to ensure quality, the availability of products, a proper feedback system, and the customization of products, thus ensuring continuity and a sustainable process. Cybersecurity ensures a risk-free cyber–physical platform with continuously upgraded and strong security standards. These criteria create challenges for supply chains due to significant increases in the investment costs of digital technologies and AI-based solutions, the high cost of energy, and the unavailability of raw materials. Other challenges are skill shortages, slow training progress, and an unprecedented rate of resignations for the frustrated unskilled workforce, putting the continuity of operations at risk.

In brief, the literature related to the industrial revolutions and supplier selection criteria offers a body of knowledge from the 1750s to 2022, highlighting that the surge of technology and the transition into digitalization are intrinsic to suppliers' progress and selection criteria. Societies have shifted from an agrarian economy to a manufacturing economy, opting for finite resources for mass production to support other new 21st-century imperatives, capitalism, and urbanization. However, according to environmentalists, the costs of industrial waste, pollutants, and toxic materials have been growing, exacerbating climate change in the 21st century. McKinsey [36] blames the supply chains of the consumer industry as being responsible for 80–90% of pollution. There have been attempts to identify the sources of pollution in a circular phenomenon, which were exercises of utter futility [37].

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