SMART GREEN MANUFACTURING

Dr. Tsai-Chi Kuo

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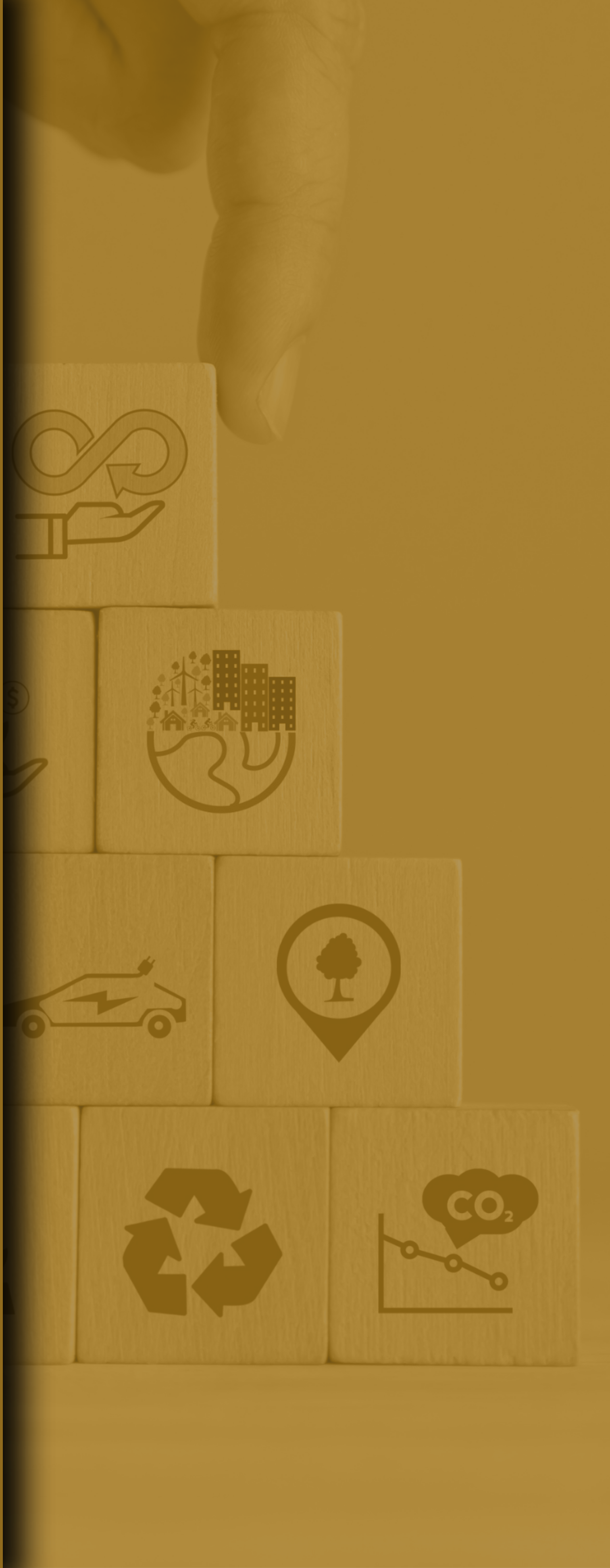

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PREFACE

The P-Insights, short for "Productivity Insights," is an extension of the Productivity Talk (P-Talk) series, which is a flagship program under the APO Secretariat's digital information initiative. Born out of both necessity and creativity under the prolonged COVID-19 pandemic, the interactive, livestreamed P-Talks bring practitioners, experts, policymakers, and ordinary citizens from all walks of life with a passion for productivity to share their experience, views, and practical tips on productivity improvement.

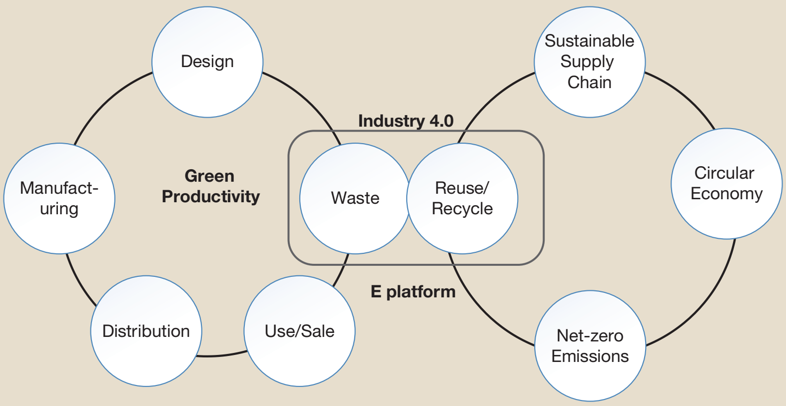
With speakers from every corner of the world, the P-Talks effectively convey productivity information to APO member countries and beyond. However, it was recognized that many of the P-Talk speakers had much more to offer beyond the 60-minute presentations and Q&A sessions that are the hallmarks of the series. To take full advantage of their broad knowledge and expertise, some were invited to elaborate on their P-Talks, resulting in this publication. It is hoped that the P-Insights will give readers a deeper understanding of the practices and applications of productivity as they are evolving during the pandemic and being adapted to meet different needs in the anticipated new normal.

INTRODUCTION

Smart green manufacturing can be seen as the integration of Industry 4.0 to achieve the "smart" goal and the implementation of a circular economy to achieve the "green" goal. In general, Green Productivity (GP) and a circular economy provide industries with a framework that includes tools and methodologies to enhance productivity, profitability, and overall growth with the least possible environmental impacts. In addition, Industry 4.0 allows business manufacturing to be smart while meeting the varied demands from the market, optimizing the resources used, constructing smart supply chains, reducing hazards, and automating operations. Figure 1 shows that GP can be enhanced using Industry 4.0.

FIGURE 1

ENHANCING GP WITH INDUSTRY 4.0.



GREEN DESIGN AND GREEN PRODUCTIVITY

Green design originally began with the concept of incorporating environmental considerations into the design stage, also known as environmentally conscious design and manufacturing (ECD&M) [1]. ECD&M is a viewpoint of manufacturing that includes social and environmental aspects to minimize the environmental impacts of a product during its life cycle stages, thereby increasing its competitiveness in the marketplace. The life cycle stages include raw materials, manufacturing, transportation, use, and waste. Green design is then expanded to GP. The central element of GP methodology is the examination and reevaluation of both production processes and products to reduce their environmental impacts and highlight ways to improve productivity and quality. More specifically, GP can simultaneously increase business profitability and decrease environmental impacts. It is said to be designed to promote overall socioeconomic development [2].

GP also covers the issues of green manufacturing. Despite the existence of different directives covering various areas from hazardous substances to global warming, many issues remain, including pollution reduction, material and resource conservation, and environmental impact reduction. The traditional objectives of GP include the process of greening supply chains, water resource management, energy efficiency management, clean development mechanisms, and solid waste management. However, there is an existing dilemma for businesses and people related to GP: how to earn a profit while protecting the environment. Therefore, a comprehensive, systematic solution has been revised and updated. It has been suggested that achieving a circular economy, net-zero emissions, and sustainable supply chain management (SSCM) are the current obstacles to achieving the environmental, social, and corporate governance goals. The terms are explained as follows.

The Circular Economy

Extended producer responsibility (EPR) was first proposed in 1991. EPR has been a driving force for the adoption of circular economy initiatives as it focuses on the end-of-life (EOL) treatment of postconsumer products. EPR is also an essential strategy for driving the circular economy while focusing on producer responsibility. The European Commission's Circular Economy Roadmap reported that “closing the loop” [3–5] on linear product life cycles of make, use, and discard and transforming them into varying loops of reuse, repair, refurbish, and recycle is a key strategy for Europe’s competitive growth into this century [6]. Therefore, an increase in the recycling rate is essential for minimizing the disposal of residues in landfills, reducing emissions, and allowing the partial recovery of raw materials used in manufacturing [7]. A circular economy is best described by the relationship between consumption and provision by the earth, which exists in an equilibrium and where there is a relatively open-ended loop, with most currently acting as a consumption sink, albeit with the possibility of further integration into a complete chain [8].

Net-zero Emissions

The greenhouse effect has led to various global problems, including extreme weather conditions and increased pressure on businesses to improve their environmental performance. To limit global warming by 1.5°C as required globally, the EU Commission proposed and adopted the European Climate Law in 2021, an agreement that aims to achieve net-zero carbon emissions for EU countries by 2050, mainly by reducing emissions, investing in green technologies, and protecting the natural environment. This agreement has been reported in several countries. To reach net zero, new technologies for global reductions in CO_2 emissions should be developed as soon as possible. Williams et al. [9] proposed three main energy system transformations to reduce 2050 greenhouse gas emissions by 80% in California below the 1990 level: end-use energy consumption; greenhouse gas intensity of electricity generation; and the electricity share of total end-use energy. Net zero could be seen as the biggest innovation opportunity concerning new technologies, such as batteries, hydrogen electrolyzers, and direct air capture and storage [10].

Sustainable Supply Chain Management

Supply chain management is “a set of three or more entities (organizations or individuals) directly involved in the upstream and downstream flow of products, services, finances, and/or information from a source to a customer” [11]. Currently, sustainability is increasingly emphasized by the academic and industry sectors. The supply chain is reformed as SSCM. Sustainable development was originally defined in 1987 by the World Commission on Environment and Development [12] in the book *Our Common Future* as: “Development that meets the needs of the present without compromising the ability of future generations to meet their own needs." In that publication, environmental issues were placed on the political agenda. Sustainability should be viewed as a balance between sustainable development and the use of natural resources, including fuel, food, land, and water. Pope et al. [13] suggested that sustainability depends on three pillars, the environment, society, and economy, which are also referred to as the triple bottom line. On occasion, they are also referred to as "people, profit, and planet." In SSCM, more collaboration and engagement are involved among supply chain members. Table 1 shows the differences between SCM and SSCM.

TABLE 1

DIFFERENCES BETWEEN SCM AND SSCM.

Category	SCM	SSCM
Integration	• Improve key performance indicators • Involve SC during planning of products, services, and marketing • Develop collaboration of SC members in production planning	• Multidimensional integration of SSCM • Forward and reverse supply chain integration • Improvement of key performance indicators
Information sharing	• Participate in customer marketing efforts • Share critical transactional information with other SC members	• Risk reduction • Competitive advantage creation and maintenance
Customer relationship	• Design business strategies with customers • Involve customers in new product decisions	• Analysis of green marketing effects on the supply chain • Competitiveness analysis • Social responsibility cooperation
Supplier relationship	• Involve suppliers in production program decisions • Promote collaborative design and analysis	• Disaster chain management • Environmental risk management • Carbon chain reduction • Collaborative design
Innovation	• Assemble the final product as close as possible to the final customer • Promote the cost model of postponement	• New business model development • Environmentally superior product development

Source: Revised with permission from Kuo et al. [14].

INDUSTRY 4.0

Recently, Industry 4.0, which was originally from Germany, has drawn considerable international attention among manufacturers engaged in connected technologies [15]. These technologies include the IoT, machine-to-machine technology, cloud computing (CC), big data analytics (BDA), and cyberphysical systems (CPS). Thus, Industry 4.0, which can be recognized as an integrated set of smart production systems, and progressive IT stand on integrated software systems [16, 17], such as smart supply chains, smart working, smart manufacturing, and smart production [18].

Basic Technologies of Industry 4.0

Through the idea of Industry 4.0, data can be collected from the physical world and added to a digital system (simulation-based) to help a decisionmaker obtain valuable opportunities for the prediction and optimization of manufacturing operations. This means that Industry 4.0 is an aid for decision-making. Therefore, some scholars have suggested constructing big data analyses and simulation modeling of customer and supplier behaviors in smart factories [19]. However, most traditional industries are not ready to migrate directly to Industry 4.0. To migrate to Industry 4.0, firms in all industries must implement multiple initiatives to investigate and exploit the benefits of digital transformation [20]. Therefore, effective solutions are required to support digital transformation, such as the transformation of business operations, product productivity, and process reengineering. The basic technologies of Industry 4.0 are described as follows:

1. IoT: The concept of the IoT is to use a number of distributed sensors (i.e., “things”) lying in an unpredictable vast environment (a house, large urban area, or greater region) [21]. These devices can collect a massive amount of raw data (structured or unstructured) and translate them into relevant information.
2. Cloud computing: CC can be accessed using web-based technologies, combining Internet connectivity and pay-per-use systems in a new

business model for IT provisioning [22, 23]. Normally, three different types of service models are categorized: infrastructure as a service; platform as a service; and software as a service.

3. Cyberphysical systems: CPS were first proposed by the US National Science Foundation in 2006. The original purpose of CPS was to reveal the fundamental scientific and engineering principles that underpin the integration of cyber and physical elements across all application sectors [24, 25].
4. Data-driven analytics (DDA): DDA involve the analysis of large volumes of heterogeneous and multisource data generated during the life cycle of industrial production [26].
5. AI: AI, according to Mayr et al. [27] is a commonly used term for engineered learning tools or perception-based modeling and also a problem-driven solution system that can be used to derive certain problems. AI is also well defined as a focus on human performance or rationality, and its implementation could benefit users. Currently, AI is used from research facilities to marketing departments and from large manufacturing industries to small farms, producing higher yields per dollar spent on using traditional equipment.

Industry 4.0 Driving Green Productivity

When considering sustainability, many studies have pointed out that data-driven Industry 4.0 can be used to solve the problems of a circular economy [28–30]. They claimed that the benefits of Industry 4.0 are vertical integration, virtualization, automation, traceability, flexibility, and energy management. Kamble et al. [31] proposed a sustainable Industry 4.0 framework. Rajput and Singh [30] attempted to identify the connection between the circular economy and Industry 4.0 in the context of the supply chain. Stock et al. [32] used Industry 4.0 as an enabler for sustainable development. Rajput and Singh [30] indicated that there are 15 challenging factors to link a circular economy and Industry 4.0: data analysis; collaborative model; CPS standards and specifications; CPS modeling and modeling integration; smart device development; investment cost; design; compatibility; infrastructure standardization; interfacing and networking; semantic interoperability; process digitization and automation; automation system virtualization; fog computation; and sensor technology.

Smart Circular Systems

The IoT changes the way value is created in the business sector as information is generated by interconnected devices, machines, and products that evolve as a fundamental component of value creation, such as maintenance, reuse, repair, and recycling. Through the IoT, there is a capability to foster the circular economy through the connection of people and things by mobile devices, offering significant economic opportunities for both individuals and businesses in multiple domains [33].

Cloud Manufacturing and Sustainable Manufacturing Processes

Cloud manufacturing increases sustainability through: 1) collaborative design; 2) greater automation; 3) improved process resilience; and 4) enhanced waste reduction, reuse, and recovery [34]. Using a cloud manufacturing model in mobility and transportation management systems, managers can reduce the total cost of services provided to residents [35].

Data-driven Analysis

Data-driven analysis can help enterprises understand their sustainability performance [36–39] and create value, i.e., value proposition, value creation and delivery, and value capture [40]. The core issue is the use of big data to create value for enterprises while reducing risks [41]. There is extensive research related to energy and cyberphysical systems. Ma et al. [24] presented an energy-cyberphysical system architecture that enables the management of energy-intensive manufacturing industries to promote the implementation of cleaner production strategies. Lu et al. [42] proposed an energy-efficient production network.

AI

AI has been implemented in both renewable and electrical energy to achieve better efficiency [43, 44]. The main advantage of AI is its ability to forecast energy consumption and optimize energy systems [45].

In summary, Industry 4.0 can enhance GP. Sharpe et al. [46] demonstrated the implementation of a CPS with EOL processing of electrical and electronic equipment. In addition, some studies have applied CPS in energy management [24, 47]. With the support of advanced technologies such as Industry 4.0, BDA, and the IoT, the optimization and different issues of green manufacturing can be resolved. Considering smart manufacturing through its three layers of perception, networks, and applications, it can acquire data from the environment and then route and transmit to different IoT hubs and devices, finally achieving a smart environment.

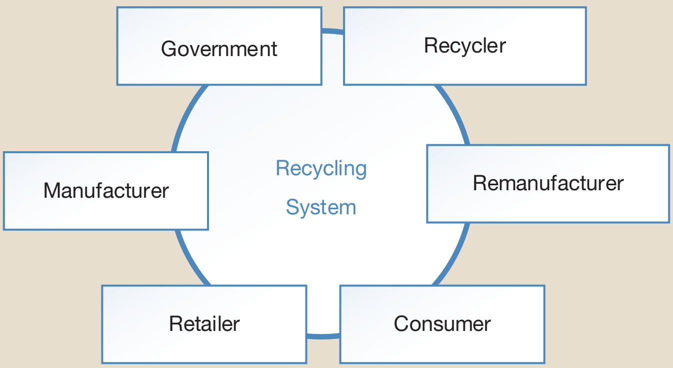
CASE STUDIES OF SMART RECYCLING AND CIRCULAR ECONOMIES

To Recycle or Not to Recycle?

Kriwet et al. [48] stated that recycling aims to close the loop of materials and components after usage by (re)using/utilizing them for new products. Recycling can also be considered a practical recycling technology or remanufacturing EOL products into useful products. A comprehensive recycling system should include the input, internal, and output stages. In the input stage, the recycling of unwanted outputs of production (internal recycling) and scrapped products both reduce the amount of waste resulting from production or consumption processes. In the output stage, recycling of unwanted outputs of production (internal recycling) and scrapped products both reduce the amount of waste resulting from production or consumption processes. The internal stage should include reverse logistics, remanufacturing, and regeneration to support real-world practices. Figure 2 shows the recycling system. Stakeholders play an important role in the

FIGURE 2

STAKEHOLDERS IN RECYCLING SYSTEMS.



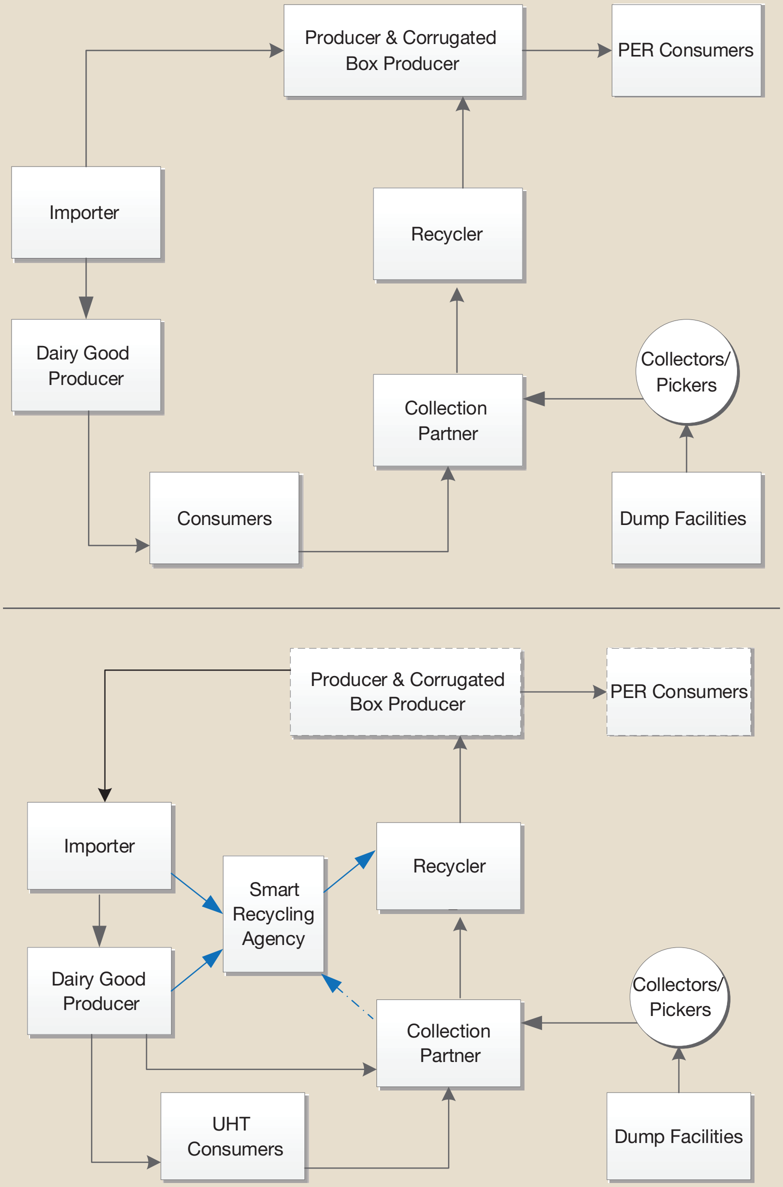
recycling framework, such as policies (government), technology development (manufacturers, remanufacturers, and recyclers), and behavior (consumers). There are three alternative approaches for manufacturers to deploy collection efforts: 1) collecting used products from consumers directly; 2) encouraging retailers to collect used products, and then purchasing those products from them; and 3) entrusting third-party logistics firms with collection [49].

Generally, manufacturers intend to design products with recycled material for environmental impact reduction. However, this intention is affected by many factors such as production methods, functional and structural requirements, market or user demands, design styles, prices, and environmental impacts. When enterprises invest resources in a recycling system, they need to overcome several problems. The first problem is to develop and coordinate efforts to create proper recycling frameworks and monitoring systems. The second problem concerns the management of financial planning, which needs to be balanced between the costs and benefits from the perspectives of recyclers and manufacturers. From a recycler's viewpoint, the recycling framework fee includes collection, sorting, reprocessing operations, and monitoring systems. These benefits include an advanced recycling fee (ARF) and salvage value. For ARFs, the recycling funding member board of the government requires the producer to pay the EOL process fee to support recycling activities. From the manufacturer's viewpoint, market demands and costs will influence the willingness to use the recycled material.

In this case, the recycling flow of an EOL Tetra Pak is illustrated. Figure 3 shows the recycling flow of an EOL Tetra Pak. As the EOL Tetra Pak can be recycled into corrugated paper or polylum boards, there is economic value in the recycling system. Previously, to manufacture corrugated paper or polylum boards, few private companies in Indonesia were granted recycling funds to maintain the recycling system based on the EPR principle. However, only certain companies have installed recycling systems. Thus, a manufacturer-led recycling alliance was established in the system with a recycling fee. In this system, the recycling rate is evaluated based on the recycling fees and recycling capacities. The main objective of this study was to investigate the APP waste recycling system, which includes a recycling framework with stakeholders and the effects of recycling funds and subsidies on the performance of recycling activities. To achieve this goal, a dynamic system model was developed for the recycling system.

FIGURE 3

AS-IS (TOP) AND TO-BE (BOTTOM) MODELS.



Source: Reproduced with permission from Kuo et al. [50].

The as-is model explained the original paper packaging system in the pulp and paper industry. The main difference between these two systems is the introduction of a recycling agent as a regulator of the recycling fund and subsidy policies, which affect the performance of recycling activities, as indicated by the changes in the recycling rate. Figure 3 shows the as-is and to-be models. In addition, the recycling fund and subsidy policies substitute for the incentives for recycling investment, which are granted to polylum ecoroof and corrugated box producers.

To Buy or to Lease?

Product service systems (PSS) emphasize user demand by delivering functions (information collection, clean clothes, mobility, warmth, and communication) without requiring ownership of physical products [51]. Therefore, customer satisfaction is solely based on the functions provided.

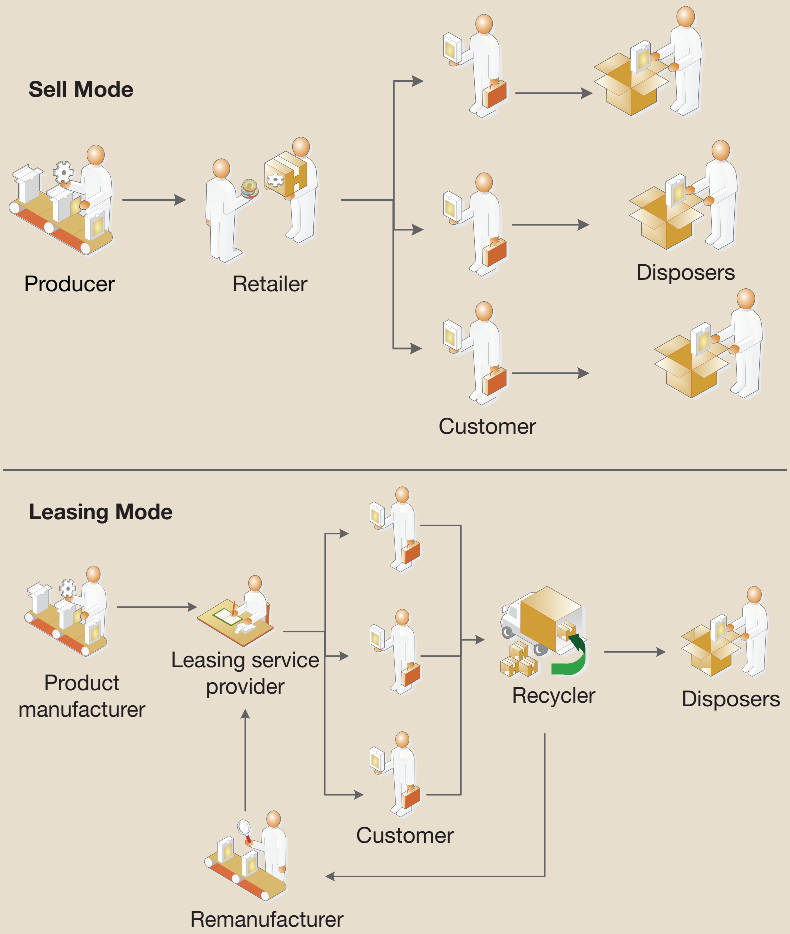
For functional sales, it is a condition that the hardware be reused, either as-is or after it has been remanufactured or recycled [52]. Under this concept, the service provider may decide how to fulfill the function that the customer is buying. This is compared with leasing, where the physical product is known or specified by the customer. Leasing emphasizes the integration of design, manufacturing, and sales. Starting from the design phase, economic design ideas play a key role in reducing the environmental impact. In the marketing phase, the focus is not on sales, but rather on achieving the reuse or reproduction of products, raw materials, or components and on enhancing the use of resources and reducing waste.

In this case, the manufacturer is considering the sell or lease mode. However, the cost evaluation is challenging. Figure 4 shows interactive connections in the sell and leasing society, which can be summarized as:

1. The sell model is a cost-based price model. A company sells the product to a customer, who then owns it. Remanufacture and recycling possibilities are lower given that the customer is responsible for product maintenance. The costs included in the sell model are construction costs, old equipment for emergencies, times profit rates, product-related costs including construction costs, repair fees, and maintenance fees for machinery and equipment.
2. The lease model is a value-based price model. A company retains ownership of the product and a customer pays leasing fees. Remanufacture

FIGURE 4

SELL MODEL (TOP) AND LEASE MODEL (BOTTOM).



and recycling possibilities are high given that the company is responsible for the product's life cycle. The costs related to leasing included leasing fees, residual values of a product, recycling benefits, repair fees of a product, maintenance fees for machinery and equipment, energy costs for using old equipment for emergencies, and disposal costs of EOL products.

In the sell model, statistical analysis shows that to increase profits, the case company needs to raise the repair and maintenance costs and reduce the cost of using old equipment. In addition, increasing installation costs and reducing maintenance costs will increase the profits. In the lease model, statistical analysis suggests that the company can increase the rent and reduce repair and maintenance costs to increase profits. Further analysis shows that when rent is increased, the company can increase the energy cost of using old equipment to raise profits. Reducing maintenance costs increases the residual value and reduces the recycling price.

CONCLUSIONS

Resource limitations and severe environmental degradation have necessitated sustainable resource utilization and environmental conservation worldwide. Industry 4.0 starts with data-driven analysis that can conceivably optimize existing infrastructure to bring sustainable solutions, reduce material usage, and reduce emissions. Furthermore, Industry 4.0 starts with the voice of the customer to articulate product requirements and then integrates different enabling technologies, such as cybertechnologies. The main purpose of Industry 4.0 is to generate value by integrating resources, services, data, and humans in real time. In general, manufacturers are just beginning to explore smart manufacturing with smart supply chains; hence, the need for the Industry 4.0 approach hinges on information sharing and communication. Information sharing also enables manufacturing process transparency and visualization. Alternatively, manufacturers could request that customers share market demand through embedded market analytics technologies to assess consumption. A good information-sharing allocation system could enhance the performance of material resource management to reduce resource waste.

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LIST OF TABLES

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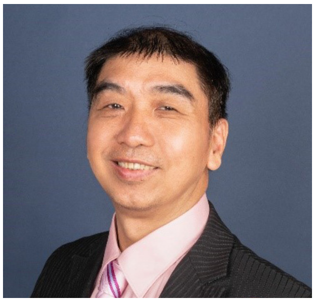

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