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Smart and Sustainable Reverse Logistics Analysis

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Abstract

Recent advances in digitalisation and information and communication technology (ICT) have not only altered the manufacturing paradigm towards the Fourth Industrial Revolution, commonly known as Industry 4.0, but have also created chances for a smart logistics revolution. The implementation of the established model led to the selection of the scenario that strikes the optimal balance between the widespread use of Industry 4.0 technologies and the required resources. The scenarios entail the incorporation of the most effective Industry 4.0 technologies, including the Internet of Things, Automated guided vehicles, Autonomous Vehicles, Artificial Intelligence, Big Data and Data Mining, Blockchain, Cloud Computing, and Electronic/Mobile Markets, and their most plausible applications. Widest feasible implementation of Industry 4.0 technology does not always guarantee the most acceptable growth scenario, and the answer should be explored in the area of shared interest among all stakeholders. Despite studies focusing on improving the smartness, connectivity, and autonomy of isolated logistics operations with a primary emphasis on the forwards channels, there is still a lack of a systematic Conceptualisation to guide the forthcoming paradigm shift of reverse logistics, such as how "Individualisation" and "service innovation" should be interpreted in a smart reverse logistics context. In order to address this void, this article defines Reverse logistics 4.0 from a holistic standpoint in order to provide a comprehensive examination of the technical influence of Industry 4.0 on reverse logistics. On the basis of published research and case studies, a conceptual framework for the transformation of smart reverse logistics is presented to combine Industry 4.0 enablers, smart service and operation transformation, and targeted sustainability objectives. A smart reverse logistics architecture is also presented to permit a high level of system integration enabled by intelligent devices and smart portals, autonomous robots, and advanced analytical tools, where the value of technological innovations can be leveraged to solve various reverse logistics issues. Through conceptual development, this study contributes by establishing a clear path and research agenda for the reverse logistics transition in Industry 4.0.

Keywords: Technological transformation, Smart technologies, Reverse supply chain.

1-Introduction

Recent societal emphasis on sustainable development and circular economy and stricter environmental restrictions have compelled businesses to assume responsibility for the whole lifespan of their goods [1].The primary objective of reverse logistics is to maximise the recovery of the remaining value from end-of-life (EOL) products by designing, operating, controlling, and maintaining effective and economic-efficient flows from customers to initial suppliers and manufacturer [167]. Non-recyclables should be disposed of in an appropriate manner. When designing and managing a reverse logistics system, economic, environmental, and social sustainability must be balanced [161-162]. However, this is not a simple task because to the difficulty of properly coordinating several stakeholders to carry out numerous processes, such as collecting, sorting, distribution, disassembly, repair, reuse, remanufacturing, recycling, energy recovery, and garbage disposal[33]. Moreover, the increased system operating costs[146], the high uncertainty related to the quantity and the quality of EOL products in the reverse flows[208], the lack of relevant and real-time information for decision-making[212-218], and the lack of coordination among different partners[146].have become some of the major.The emerging concept of Industry 4.0 and its enabling technologies provide new opportunities for achieving improved internet-based connectivity, smartness, intelligence, and autonomous operations of not only manufacturing processes but also logistics systems, making it possible to better address these challenges[15]. In recent years, the notion of Logistics 4.0 has also been advocated, capitalising on the technical innovation of the Fourth Industrial Revolution [212-218].

A Logistics 4.0 system can achieve real-time monitoring and decision-making, responsive communications, improved resource allocation, and smoother material flows by combining multiple cutting-edge technologies, such as internet of things(IOT), big data analytics, and artificial intelligence (AI), in a cyber-physical system (CPS) that integrates both computational intelligence and smart physical assets. These intelligent technologies may also be used to enhance the economic, environmental, and social sustainability of reverse logistics systems.Changes in demand and the incorporation of various Industry 4.0 technologies will lead to a paradigm change in reverse logistics, with the former serving as the catalyst and the latter as the facilitator of this intelligent and sustainable transition. Increased data availability may enhance the forecast and traceability of end-of-life (EOL) items, hence reducing the uncertainty of reverse flows and enhancing the planning of various activities, such as collection [217].and remanufacturing [212-218]. High-quality data significantly enhances the outputs of model-based optimisation and simulation techniques for crucial choices [218]. Collection scheduling, routeing, inventory management, and distribution. In addition, the expanded usage of AI-enabled smart robots may replace human labour in difficult environments, and the greater interaction between various partners and stakeholders through a highly linked digital platform may improve inter-company information exchange and resource utilisation.Many sustainability studies have focused on reverse logistics (RL) due to a lack of raw materials,rising environmental pollution, increased social responsibility, environmental legislation, and market shifts[4]. The development of RL systems is the primary requirement and precondition for constructing the closed-loop supply chain (CLSC), a kind of supply chain that conforms to the Circular Economy idea (CE). Initially, RL and CLSC research was motivated by public consciousness, i.e., the difficulties caused by the return flows to ordinary people and the environment [41-42]. With the rise of the consumer society, the shortening of product lifetimes, and public pressure to tackle the difficulties produced by end-of-life items, the legislative authorities establish a variety of laws and directives regulating this field [62]. Finally, RL and CLSC have been identified as revenue-generating opportunities for several supply chain actors [73]. Demands for the supply of services as well as suppliers of these services are developing, indicating the formation of a market centred on RL. Therefore, the objective is to develop a sustainable RL system that is aligned with the objectives and interests of the key players, including service providers, service consumers, administrations, and citizens. They gain from this system through the reduction of waste disposal, the increase and recovery of product value and energy, the extension of the product life cycle, the extraction and recycling of materials, the creation of a competitive advantage, the acceleration of return on investment, the improvement of customer relations, and the reduction of transport emissions[209].Traditional RL systems provide all of these great impacts, but they must be modernised to make them more efficient, economical, and acceptable. By implementing numerous Industry 4.0 technologies, such as the Internet of Things, Cloud Computing, Autonomous cars, Artificial Intelligence, etc., RL systems may be considerably enhanced and updated, generating smart RL systems. RL can be defined as the application of various Industry 4.0 technologies to manage complex flows of physical items, cash, data, and information at various stages of the reverse portion of the supply chain in order to maximise the value and material recovery from returned or waste products[108-109].Consequently, this research focuses on the formulation and assessment of smart RL system development scenarios, taking into consideration the level of development of Industry 4.0 technologies, their applicability, and the social, economic, technical, and sustainability trends. The objective is to pick the one with the highest probability of success, broadest applicability, and most positive benefits, which would serve as a decision-making framework in the process of developing a sustainable, smart RL system acceptable to all major stakeholders.

Consequently, the scenario that offers the optimal balance between the widespread deployment of Industry 4.0 technologies and the required resources for its development and implementation is chosen. The findings suggest that the broadest possible use of Industry 4.0 technology does not always guarantee the most desirable development scenarios, and that the choice should be taken by reaching a compromise between the interests of all parties involved. This research established a unique hybrid multi-criteria decision-making (MCDM) model that integrates Delphi, ANP, and COBRA approaches in a fuzzy environment in order to answer the given issue.No major progress towards the creation of smart RL using multiple Industry 4.0 technologies to optimise and increase return flows has been achieved in prior research dealing with the subjects addressed in this study. In addition, there are no research on the simultaneous uses of different technologies for executing numerous operations in multiple phases of RL. As for the created model, the COBRA approach has not before been applied to fuzzy environments, nor have these three methods been integrated. Consequently, the design of intelligent RL scenarios, the framework for evaluating and rating them, and the development of an unique MCDM model are the primary contributions of this research.Even though recent studies have demonstrated the application of several Industry 4.0 technologies in isolated reverse logistics operations, a systematic conceptual framework is still lacking to better understand the potential and implications of these technological innovations for the entire reverse logistics system, particularly from the perspective of service innovation. How, for instance, should "individualisation" be construed in the context of smart reverse logistics? In addition, the majority of studies stress solely the advantages of adopting Industry 4.0, but the constraints of technology adoption in reverse logistics systems have received significantly less attention.

2-Background research and Outline

Before defining the problem's structure and solution methodology, it is required to define smart RL and offer an overview of the approaches utilised to construct the methodology. Accordingly, the next section describes the study's context.

2-1- Backwards logistics

In the late 1980s and early 1990s of the previous century, the phrase "Reverse logistics" emerged and started to be used more often in writing [150-151]. This term's meaning has developed through time, and its meanings have altered appropriately. One of the early definitions of RL described it as "the area including the talents and actions associated in the management of trash, transportation and disposal of items and containers"[106]. Thierry et al. defined RL as the "management of used or abandoned goods, components, and materials with the goal of maximising economic and environmental value while minimising waste." One of the first contemporary definitions of RL was "a collection of management initiatives to reinsert non-core assets in value-added industries"[18]. RL is the process of planning, implementing, and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods, and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal [91]. RL is a sort of supply chain management that tries to optimise the movement of products or materials from the end user to the seller or manufacturer while retaining their values.Although the term RL has been in use for a long time and the topic of various studies, its significance increased with the advent of the notion of Circular Economy (CE). In the older "take-make-dispose" philosophy of production, RL was seen as an inescapable burden that produces extra costs and complicates supply chains. However, with the advent of CE, RL has become one of the primary instruments for developing diverse sustainable solutions and business models [93-95]. This has resulted in the increase of study into different elements of RL, the most significant of which are network design [66-69], implementation choices [10].and RL's impact on society [10]. RL network nodes placement [44], routeing and scheduling [99], performance [99], and information management [99] etc. The introduction of the idea of Industry 4.0 [158-159] has enabled advancements in all the aforementioned sectors of RL research. e. Innovative technologies that constitute the "flywheel" of this notion. This study aims to fill a vacuum in the literature by investigating the development of smart RL, which would entail the integration of various technologies for the purpose of optimising and increasing the efficiency of return flows.

2-2- Technologies of Industry 4.0 in reverse logistics

The notion of Industry 4.0 technologies play a crucial role in the preservation of these values. Industry 4.0 is a concept that has surfaced in the literature and begun to gain popularity over the last decade [108-109]. As this is a developing field, there are several definitions, one of which is that Industry 4.0 refers to "complex solutions generated in the realm of shared interest of engineering, computer science, and management" [63].Regardless of the definition, what essentially characterises the notion of Industry 4.0 is the creation and implementation of contemporary technologies, as well as the discovery of new methods to link and utilise existing technology. Internet of Things (IOT), Automated guided vehicles (AGV), Autonomous Vehicles (AV), Artificial Intelligence (AI), Big Data and Data Mining (BD&DM), Blockchain (BC), Cloud Computing (CC), Electronic/Mobile marketplaces (E/M marketplaces), three-dimensional printing 3D printing), and Advanced Robotics are recent applications of Industry 4.0 technologies in the RL sector (AR).IOT, also known as "embedded internet", "pervasive computing", "physical internet", and "cyber physical system", is a hypernym for "various aspects of Internet and network integration with the physical world with the goal of providing communication and connections, in space and time, to all system elements" [120-126]. Some of the most significant applications of the IOT in RL identified in the literature thus far include designing an RL system [30], an information system [20], a waste collection system[203-205], a reverse supply chain managements system [59-60]of-life products evaluations system[92][165-166].AGVs, also known as "self-guided vehicles," are "transportation and material handling devices remotely or autonomously operated by magnets, radio waves, lasers, and cameras, etc." [96]. they are mostly used in RL to execute intra-logistics and material-handling tasks inside RL network nodes [56]. The objective is to simplify and improve the reliability and efficacy of these processes by automation and minimum human intervention [141].AVs are vehicles "capable of adapting, learning, and operating themselves without any or minimal human interaction"[108-109]; they can "detect their surrounding environment, make autonomous judgements, and navigate safely through it" In RL, road and aerial AVs are mostly used for short-haul transport and first/last mile deliveries, while rail and waterborne AVs are predominantly utilised for long-haul transport between RL network nodes [27]. Utilizing AVs increases productivity and efficiency while decreasing expenses and the need for human resources in the transport operations inside the RL networks [183-184].AI is the ability of computers to act in a manner requiring intelligence and judgement, which are often attributed to humans. AI allows a number of other significant intelligent technologies, including Ambient Intelligence, Virtual Reality, Augmented Reality, and, therefore, Extended Reality. In the field of RL, they may be used for network design, aid with the implementation of operations like as collection, sorting, inspection, disassembly, recycling, remanufacturing, redistribution, vehicle routeing, product return predictions, and so on[224-225].These technologies provide improved accuracy, efficiency, safety, timeliness, automation, etc. for less money in relation to RL operations and processes[86].BD refers to "data sets that are so large and complicated that typical data processing technologies cannot gather, manage, and analyse them in a reasonable length of time"[228]. DM is "the procedures of sifting through massive data sets to uncover patterns and relationships that might aid in the resolution of business challenges through data analysis"[28].As these technologies are often employed together in practise, they are treated as a single integrated technology in this research. The most significant applications of this technology in the field of RL include network design [66-69], predicting returns and estimating their quality, deciding on their further processing[153-154], speeding up [229-232]and estimating the performance of various RL activities[12-14], etc. For extensive RL flows that occur every day, data on locations, structure of goods and materials, delivery sizes, starting and ending points, etc. are tracked, recorded, and stored, thereby forming extremely useful BD sets that are then processed and analysed using DM to provide operational information to decision makers in the form of thresholds, key performance indicators, parameters, etc[21].BC refers to "the data base comprising of numerous smaller bases (blocks) storing information on digital transactions and interconnected to build chains"[185]. Smart contracting is one of the most significant applications of BD in the RL industry [187].the implementation of traceability and transparency in RL processes [144], the management of supplier/customer interactions [49]. The primary objective of using this technology is to improve interoperability and confidence in RL networks and allow businesses to compete effectively in the market [212-218].CC is "a model that enables ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (such as networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction" [130]. The implementation of cloud-based solutions for managing numerous processes and activities. Allows the development of an intelligent RL management system [40]. The most apparent motivations for using this technology are resource conservation and dispersed cooperation among RL players.E/M markets are the electronic platforms that employ the Internet and different technologies for smart mobile devices to conduct business transactions. In RL, E/M-marketplaces allow market defragmentation, installation of return aggregators, formulation of appropriate return rules, building of an effective RL information system, diversification of RL modes.

The use of pervasive and easily accessible smart mobile devices and high-speed internet enables the reduction of uncertainty, treatment costs, complexity, and processing time for return products purchased from E/M marketplaces, while improving visibility, automation, and control of the return processes .3D printing, often known as "additive manufacturing," is a production technique that involves progressively adding layers of material to a computer-generated model. This technology is important for RL because a substantial portion of return flows may be employed as raw materials for the manufacturing of new goods. Utilization of returned goods as raw materials offers reliable, uninterrupted, and independent supply while minimising waste, transport costs, negative impacts of transit .AR is a complex technology that mixes clever programming and powerful hardware and use smart sensors to interact with real-world situations and execute human-like activities. In conjunction with other Industry 4.0 technologies, they grew "smarter," able to "see," "think," freely move, interact with their surroundings, and execute increasingly sophisticated operations [37]. Within the nodes of RL networks, robots may be utilised for the collection, transportation, categorisation, disassembly, storage, and retrieval of returned items [177-178]. Greater process efficiency, adaptability, dependability, and accuracy are the primary reasons for the use of this technology in RL[37].Until now, the majority of research papers have investigated the use of a single technology, or at most two technologies, and their application at some point of RL processes. This study aims to fill a gap in the literature by attempting a complete assessment of the different uses of various technologies and the definition of potential scenarios for the development of smart reverse logistics.

2-3- Examine the MCDM approaches included into the model

In a fuzzy context, the newly suggested MCDM model incorporates the Delphi, ANP, and COBRA approaches. The fuzzy DANP technique is used to determine the weights of the criterion, while the fuzzy COBRA approach is used to rank the alternatives. Following is a summary of the primary characteristics and applications of these techniques.Saaty developed the ANP technique, which represents a decision-making issue as a network, allowing for more complicated interrelationships with interdependencies and feedback relationships among the problem pieces (criteria, sub-criteria, and alternatives). The ANP constructs a network by arranging the components into clusters and defining the relationships inside and between them (inner and outer dependencies) [232]. Most approaches derive the criterion weights by collecting the values while assuming the autonomy of criteria, which often does not represent real-world circumstances in which the criteria are interdependent and interconnected [231].In reality, this is the primary benefit of the ANP technique, which is the ability to evaluate complicated direct and indirect relationships between the issue's aspects, so enabling a holistic understanding of the decision-making challenge[78].In addition, it permits the examination of both quantitative and qualitative factors and assures assessment uniformity. Since the topic addressed in this research requires the construction of interdependent criteria and sub-criteria, it was appropriate and justifiable to apply the ANP approach to determine the weights of these components. The incapacity of ANP and other traditional MCDM approaches to cope with the ambiguity and vagueness of human ideas is one of its primary drawbacks. To circumvent this, fuzzy logic has been included into the ANP technique, making it more adaptable and precise. The ANP method is widely used and has recently been applied in a variety of fields, both in its conventional form [45].and in a fuzzy environment, either alone or in conjunction with other methods or in conjunction with other techniques.Dalkey and Helmer's Delphi method reaches agreement on a topic or decision-making issue by the establishment of groups whose members have the ability to evaluate, but also modify their ideas depending on the input from the other members' evaluations [131]. It is described as "a process of systematic solicitation and collecting of judgements on a given issue using a series of precisely crafted sequential questions, interspersed with summary material and feedback on views drawn from prior replies"[34]. The Delphi method allows the decision-makers (DMs) to remain anonymous, it reaches the results through multiple iterations, thereby increasing the reliability, it controls the feedback information in the decision process, thereby increasing the stability of the DMs' responses, and it utilises statistical measures to ensure group consensus [238].However, it requires substantial financial and time resources, as well as an effort to assure a high rate of questionnaire return and processing of the imprecise, unclear, and ambiguous assessments of the DMs.To remedy these drawbacks, Ishikawa et al. included fuzzy logic into the Delphi technique, allowing for a quicker convergence of the experts' judgements and a more trustworthy consideration of their approximate and uncertain assessments[103]. In this research, fuzzy Delphi is utilised to consolidate the opinions of experts about the defined criteria. Although integration of fuzzy Delphi and fuzzy ANP is not original [239]. There are no studies that apply this integrated technique to the reverse logistics sector, which is another research need that this work seeks to address.

2-4- The cutting-edge state of the art Backwards logistics

Reverse logistics focuses on the recovery of value from end-of-life items and the responsible disposal of nonrecyclables. Reuse and recycling processes date back a very long time; for instance, following appropriate cleaning and treatment, beverage makers may reuse returned bottles many times for new goods. In the early 1990s, the idea of reverse logistics was introduced to describe all important activities and logistical flows from final consumers to various producers, recyclers, and other players[173].The primary functions of a reverse logistics system are the collection of end-of-life (EOL) products from customers and end-users, the appropriate inspection, sorting, disassembly, and/or pre-processing, the distribution of various products, parts, and components to respective facilities for proper treatment, and the planning and scheduling of facility operations and transportation[3].Configuring a reverse logistics system for the efficient administration of these activities needs strategic, tactical, and operational-level decision-making. Extensive research has been conducted over the past three decades to improve conceptual development [41-42].formulate advanced mathematical models and algorithms [38], provide empirical studies and implications [220], and develop additional qualitative and quantitative methods for supporting various decisions in reverse logistics [220]. Initially, the impetus for reverse logistics stems from two factor [54]. From an ecological standpoint, reverse logistics may increase the consumption of various commodities, hence aiding in the resolution of global resource depletion issues. In addition, product recovery may give firms with chances to reduce costs and increase profitability. In practise, however, the value recovery through reverse logistics may be severely hampered by a number of factors, including the low-profit margin [163], the possibility of competition from new products or market cannibalization [9]. The unpredictability of market acceptance [23], and the complexity of managing reverse flows. In addition, despite the fact that reverse logistics has been seen as an integral aspect of sustainable development and the circular economy, incorrect recycling practises may have detrimental environmental and social effects[93-95]. For instance, the large export volume of waste electrical and electronic equipment (WEEE) from developed countries, such as the United States, the European Union, and Japan, to developing countries in south-east Asia not only causes increased glasshouse gas (GHG) emissions related to maritime transportation, but also poses significant risks to workers and the environment due to the primitive and low-tech recycling methods employed. Therefore, the efficient design of a reverse logistics system will contribute to the promotion of more sustainable practises across a variety of activities.The chart in Figure 1 displays a keyword co-occurrence analysis of recent articles on reverse logistics. The Web of Science (WOS) database was used to search for relevant articles in order to create the graphic. Recent research on reverse logistics has been on managing different kinds of end-of-life (EOL) items via a variety of solutions that take economic, social, and environmental performance into account. Several crucial decisions, such as facility location, transportation, and vehicle routeing, have been addressed primarily through the use of advanced quantitative methods, such as mathematical models[66-69], multi-criteria decision support methods, and simulation;Goncalves et al;Pandian and Abdul-Karim . Among them, optimisation is the most prevalent method for resolving complicated decision-making issues in reverse logistics. Early research focuses on the development of deterministic single-objective optimisation models for decreasing system operational costs or maximising overall profits [69]. Recent studies, however, emphasise the balance among different sustainable indicators with multi-objective optimisation models; the proper formulation and treatment of uncertainties [51], the improvement of the models' computational efficiency [2], and the management of.

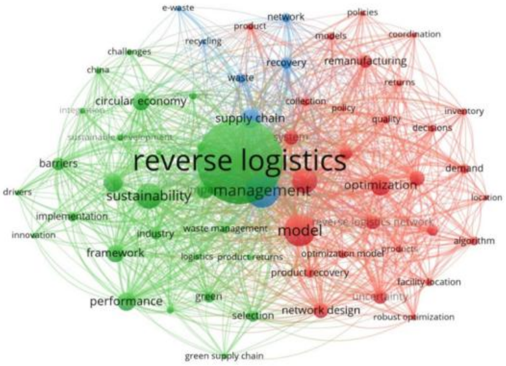

Fig 1-An examination of reverse logistics keyword co-occurrence

2-5- Industrial Revolution 4.0

Industry 4.0, also known as the Fourth Industrial Revolution, was proposed in 2011 by German researchers and industrial practitioners [49].who presented the blueprint for the next generation of manufacturing systems based on the adoption of cutting-edge manufacturing technologies and ICT. Even though Industry 4.0 is a novel idea, it has been extensively studied by scholars throughout the globe over the last decade owing to its potential to significantly alter the paradigms of almost all sectors and enterprises via digital transformation. On the one hand, the present shift in the industrial paradigm is driven by new demands for enhanced product and service individualisation, a reduced time-to-market, small-scale decentralised client groups, etc. On the other hand, these new demand patterns can be addressed more effectively with the help of recent technological developments that have enabled businesses to achieve a highly flexible, agile, responsive, and resource-efficient manufacturing process via digitalisation and various smart technologies [116]. Compared to the Third Industrial Revolution, which began in the early 1970s and utilised industrial robots, advanced machine tools, computer-aided manufacturing (CAM), and lean production to achieve mass customization through increased automation, reconfigurability, and flexibility, Industry 4.0 possesses a number of novel characteristics. Technologically, an Industry 4.0 production system stresses the internet/5G-based communication and networking of various smart devices and cyber components, which enables real-time data collecting, autonomous system control, and efficient human-machine interaction [174]. The computational intelligence offered by AI, big data analytics, and enhanced optimisation and simulation tools, which allows greater prediction and real-time data-driven decision-making, is another important aspect. These Industry 4.0 technologies open the way for new business models, personalised customisation, improved resource sharing, and sustainable manufacturing from a commercial standpoint[12].Based on Salkin et al. Bai et al, Frank et al, and Phuyal et al, Figure 2 categorises the important Industry 4.0 technologies into the physical layer, the cyber layer, and the cyber-physical layer. The dramatic growth in linked device use has accelerated the digital transition. Recent study indicates that the overall number of linked devices in the globe has expanded about 99-fold over the previous two decades, and that the average number of connected devices per person will reach around 6.58 by 2020. A manufacturing system enabled by Industry 4.0 consists of a large number of diverse smart and connected robots and equipment that communicate with one another and interact with cyber intelligence in real time. A CPS's complexity, connectedness, intelligence, and autonomy are determined by the amount of integration between its physical and cyber components. Lee ET al.identified five stages of technological integration inside a CPS: machine-level connection, data transmission and conversion, system-level connectivity, system cognition, and system intelligence and self-configuration. A smart manufacturing system with the highest level of CPS is able to make self-decisions based on individual customer orders, generate production procedures, test various scenarios in virtual environments, and control intelligent robots and machines for an autonomous and highly responsive production process.

Figure 3 depicts the keyword co-occurrence analysis of current Industry 4.0-related research. Priority has been given to the technical advancement of CPS, IOT, AI, big data analytics, blockchain, additive manufacturing, etc., in order to achieve predictive maintenance, real-time decision-making, smart manufacturing, and improved production management and planning. In addition to improving manufacturing processes, these technologies are also utilised to improve supply chain management [48], innovation [125], and sustainable development. Recent research has uncovered numerous opportunities to improve sustainability and circular economy with the help of Industry 4.0[12].such as reducing waste generation and increasing material utilisation by adopting a demand-driven, small-scale intelligent production process with additive manufacturing[55].Contributions of this study to the field.Even though Industry 4.0 has provided new opportunities for improving decision-making and operations with better use of smart devices, data analytics, and computational intelligence, their adoption in reverse logistics is still in its infancy and has not been widely discussed in the literature, as evidenced by a comparison of these keywords. For instance, several optimisation models have been created to enhance decision-making in reverse logistics; nevertheless, the outcomes of these models are highly reliant on the availability and quality of input data. Due to the substantial uncertainty associated with the input parameters, these models will be computationally costly to solve in polynomial time. In addition, the accuracy of the models' outputs and the resulting conclusions may be substantially altered. Due to these factors, the use of Industry 4.0 technologies for their effects on enhancing data quality, computational intelligence, and reverse logistics operations is well-justified.

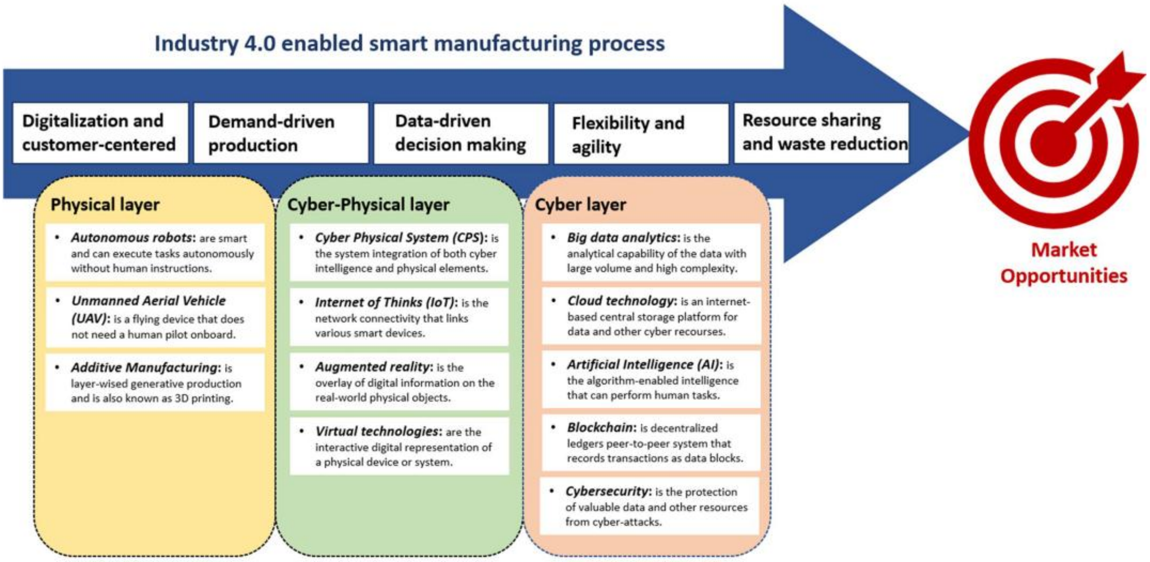

Fig 2-Smart manufacturing enabled by Industry 4.0

This paper aims to provide a systematic conceptual development and research agenda for the smart and sustainable transformation of reverse logistics in Industry 4.0, referred to as Reverse Logistics 4.0, based on both theoretical and practical insights relating to different reverse logistics activities. This paper's contributions may be summarised as follows:

- Reverse Logistics 4.0 is defined with both technical improvement and service innovation in mind.
- The conceptual foundation for the intelligent and sustainable transformation of Reverse Logistics 4.0 is created.
- The research agenda for the transition to intelligent and sustainable Reverse Logistics 4.0 is provided.

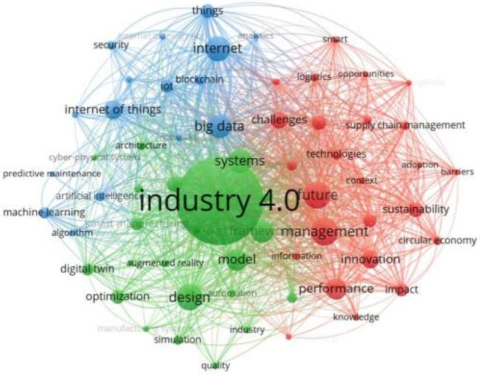

Fig 3- Keyword co-occurrence analysis of Industry 4.0

2-6- Reverse Logistics4.0

On the basis of the conceptual development of Logistics 4.0, this part defines the notion of Reverse Logistics 4.0.

Today, "4.0" is extensively used not just in the manufacturing business but also in a variety of other disciplines to characterise future paradigm changes brought about by digitalisation and sophisticated ICT. Adopting the technical advancements of Industry 4.0, the idea of Logistical 4.0 was introduced for the first time in, emphasising the real-time capability, rapid decision support, and convertibility of a new IT system enabled by CPS to support logistics choices. Regarding the four Industrial Revolutions in history, Wang [214] summarised the four logistics evolution stages as the mechanisation of transportation (Logistics 1.0), the automation of logistics operations (Logistics 2.0), the advancement of logistics management systems (Logistics 3.0), and the intelligent and autonomous logistics systems (Logistics 4.0), respectively. Several researchers contend that the objective of Logistics 4.0 is to digitise and automate the logistics processes and operations using CPS, whose technological architecture consists of six layers: the physical asset layer, the data acquisition layer with sensors and middleware, the control layer, the database layer, the analytical and decision support layer, and the management layer. From the standpoint of business innovation, Logistics 4.0 is considered as a conceptual extension of Industry 4.0, whose key characteristics have been the subject of several studies [45].

- Demand-driven individualisation and customization: Value proposition by meeting highly personalised client requests through CPS, customer-involved design, additive manufacturing, pull production, and logistics.
- Product-service architecture: Rolls-TotalCare® Royce's initiative, also known as Powered-by-the-hours, has assisted in achieving a win-win situation for both the airlines and the jet engine manufacturer by shifting towards the greater sale of services rather than goods.

Increased digitisation promotes efficient communication between people and machines and contributes to the convergence of the real and virtual worlds.

- Autonomous operations: With the support of IOT, CPS, AI, UAV, and smart robots, many logistical activities, such as material handling and transportation, will become more autonomous.
- Resource sharing: The real-time data collection and analytical power enabled by IOT, AI, and advanced optimisation increase the level of resource sharing among different stakeholders in a logistics system, which may offset the increased cost and environmental impacts associated with satisfying small-scale, individualised, and geographically dispersed customer demands for a high level of service.
- Green and sustainable logistics: Waste creation may be decreased using on-demand and additive manufacturing, and the environmental consequences of diverse logistical activities can be better monitored and avoided with blockchain technology.Increased digitisation and system integration at both the intraand inter-enterprise levels are necessary to support efficient stakeholder interactions, greater data use, real-time decision-making, simplified operations, and enhanced resource utilisation in a logistics system. Recently, the conceptual development of Logistics 4.0 trends to synchronise business innovations with technological advancements, where business innovations are considered the objectives of the next generation of smart logistic systems and technological advancements are believed to be the enablers for achieving these objectives. According to Winkelhaus and Grosse, Logistics 4.0 refers to smart technologies that enable cost-effective and highly responsive logistics services for individualisation and customization. To further facilitate the adoption of the concept of Logistics 4.0, studies have been conducted to provide implications on the use of various Industry 4.0 technologies in various logistics operations, to establish models for measuring the maturity level of Logistics 4.0 and to comprehend the relevant human factors and learning effects [47].

3- The effect of Reverse Logistics4.0

Even though Logistics 4.0 has been significantly addressed in recent years, reverse logistics has not received as much study attention [196-199]. On the one hand, a number of Industry 4.0 technologies may help reverse logistics operations similarly to how they assist forwards logistics. On the other hand, forwards logistics and reverse logistics have very different aims and procedures. For instance, the business objective of a Logistics 4.0 system is to achieve the value proposition by providing highly individualised products and responsive services, but for a reverse logistics system, the purpose may be different or the meaning of individualisation may need to be interpreted differently, such as a smart waste management system with an individualised collection schedule. Consequently, it is essential to give a comprehensive grasp of Reverse Logistics 4.0.Recent years have seen an increase in initiatives to enhance the sustainability and operations of reverse logistics using Industry 4.0 technologies, such as real-time information exchange and the dissemination of green goods[35-36]. From the standpoint of conceptual development, Figure 4 depicts a systematic paradigm shift in reverse logistics in relation to the four industrial revolutions. Even though reverse logistics was not envisioned until the early 1990s, associated actions, such as part recycling and garbage disposal, were widespread.

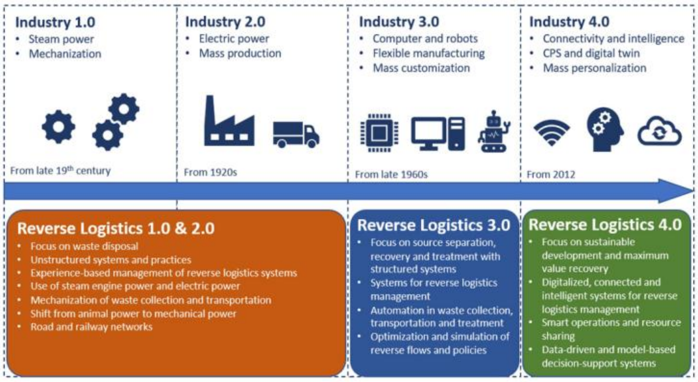

Fig 4- Evolution of reverse logistics in comparison to the four Industrial Revolutions

Beginning in the early nineteenth century, modern industry led to a rise in population and fast urbanisation, which generated a market for used goods and increased the demand for sophisticated reverse logistics networks. London, United Kingdom, built an early coordinated material recycling and waste management system to ensure urban cleanliness and quality of life. Using widespread mechanisation, steam power, and electricity, the first two industrial revolutions influenced the collection, transportation, and disposal of trash similarly to how they affected other industries. At that time, however, the primary destinations for old things were either secondhand markets or landfills, and recycling was not commonly done. As environmental pollution and resource depletion became more of a concern, the emphasis of reverse logistics switched from waste disposal to resource recovery by means of improved source separation and enhanced reuse, remanufacturing, and recycling operations. Industry 3.0's developments in computing and robotics improved decision-making assistance with enhanced optimisation, modelling, and geographic information system (GIS), and automated different reverse logistics activities. In addition, the improved reconfigurability and flexibility of manufacturing systems not only enable mass customisation, but also open the way for flexible remanufacturing in reverse logistics. During this time period, the emphasis was on redirecting EOL product flows from landfills to other value recovery options, and reverse logistics was designed to show the necessary activities and flows associated with the proper management of EOL goods [54].

Through a comprehensive trade-off analysis, not only the economic advantages of product recovery but also the environmental and social performances of the whole reverse logistics system have received increased attention over the last decade [68]. In addition, technology improvements have enabled digital and intelligent solutions to alter the paradigms of reverse logistics in three primary ways: data, services, and operations. Adopting IOT, smart devices, AI, and big data analytics has unearthed the value of data in an unprecedented manner, enabling improved and real-time planning of various resources and activities. The interactive and intelligent digital platform in the cloud links various service providers and clients in order to maximise resource sharing and create novel services. The importance of consumer participation in reverse logistics is growing, which gives greater data on the quality, quantity, timing, and location of the return of various EOL items [217]. In addition, the deployment of AI-enabled intelligent robots and vehicles makes reverse logistics operations more autonomous. Consequently, the idea of Reverse Logistics 4.0 is defined as follows, based on these characteristics: Reverse Logistics 4.0 is the sustainable management of all necessary flows and activities for value recovery and/or correct disposal of end-of-life (EOL) items via individualisation enabled by data-driven and intelligent technology and novel services.

Reverse Logistics 4.0 stresses the use of data and smart technology to actualise novel reverse logistics services and to establish harmony between the three pillars of sustainable development,namely economic efficiency,environmental friendliness, and social responsibility. Individualization represents service smartness and innovations in the framework of Reverse Logistics 4.0, whose needs are either pushed by customers, e.g., customised collection[198],or driven by product and data, e.g., data-driven remanufacturing of WEEE[218].An individual collection and remanufacturing operation, for instance, may be planned and optimised based on the real-time information of the EOL product flows, such as product type, material, structure, and quality level, and the company's available resources.

3-1- Intelligent and sustainable transformation of reverse logistics

Based on the definition of Reverse Logistics 4.0, Figure 5 illustrates a conceptual framework for smart reverse logistics transformation, highlighting the role of Industry 4.0 technologies in defining reverse logistics service and operations, as well as the three pillars of sustainable development. The conceptual framework for Reverse Logistics 4.0 is comprised of four basic elements:

1. The main technologies of Industry 4.0, including as IOT, CPS, AI, and autonomous robots, are catalysts for the smart reverse logistics revolution.

Adopting disruptive technology impacts the five primary reverse logistics operations, namely collection of end-of-life (EOL) items, sorting and pre-processing, transportation, value recovery via remanufacturing and recycling, and disposal.

The enhancement of reverse logistics service and operations is concentrated on the transformation of reverse logistics.

The triple-bottom-line focus areas for enhancing the economic, environmental, and social sustainability of reverse logistics.

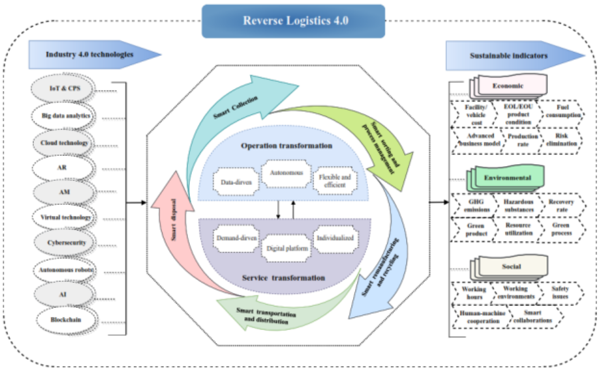

Fig 5- A conceptual framework for the intelligent and sustainable transformation of reverse logistics in Reverse Logistics 4.0

This conceptual framework depicts clearly the relationships between technical enablers, reverse logistics processes and transformations, and sustainability objectives. With the rising use of Industry 4.0 technologies, Reverse Logistics 4.0 is at the core of the transformation of reverse logistics service and operations:

- Smart service transformation: The fundamental driver of Reverse Logistics 4.0 is a transformation that is demand-driven and service-oriented. To optimise consumer value and service, it is possible, for instance, to provide tailored collecting services for old items. However, offering such a service in a conventional reverse logistics system is often costly and involves a substantial increase in resource commitments. Thus, a digitalized platform may promote real-time communication and information exchange across many stakeholders, and a data-driven intelligent decision support system may improve resource allocation and usage, allowing for the efficient delivery of personalised services.

- Smart operation transformation: Data-driven and autonomous operations are the key enablers of Reverse Logistics 4.0 to offset the increased costs of providing a high level of personalised service, improve operational effectiveness and resource efficiency, minimise downtime, reduce risks and harshnesses in the working environment, etc. For instance, using both predictive and real-time data, the collecting, transportation, and remanufacturing of discarded items may be better organised. Moreover, the operations and working environment of different reverse logistics tasks may be enhanced, for instance, by using AI-enabled intelligent robots for extremely accurate and autonomous garbage sorting.

The logic of this conceptual framework reveals that smart service and operation reforms throughout all phases of a reverse logistics system are primarily driven by the improved achievement of specific sustainability objectives, while Industry 4.0 technologies are the most crucial enablers. Notable in this smart paradigm shift is that embracing new and disruptive technology is not the objective, but rather a tool to allow responsive services and effective procedures. In the meanwhile, technology alone will not improve the system performance of a reverse logistics system, but the transformation and redesign of service and operations may enhance the economic, environmental, and social aspects of sustainability. In this sense, this conceptual framework facilitates a better understanding of the implementation of Industry 4.0 technologies across a variety of smart reverse logistics activities. Based on an examination of the relevant literature and case studies,

3-2- Smart collection

Even if routes can be routinely improved in a conventional system for collecting EOL products, the inherent unpredictability may lead to a resource allocation issue that necessitates a compromise between operational costs and service levels. For instance, the collection of EOL products and other forms of garbage on set schedules and routes often results in inefficient resource use, excessive fuel consumption, and poor service quality [120-126]. In addition, the poor service level of biodegrade waste may lead to the buildup of germs from offensive smells and the spread of illness. To combat this issue, smart bins equipped with IOT sensors are increasingly being utilised to monitor and give real-time data regarding their fill levels and locations, allowing collection routes to be dynamically adjusted and digitally updated. Built an IOT-driven Kanban system for the collecting of EOL items. John et al. developed another IOT-enabled prediction and monitoring system that could be put in the current collecting bins of various sizes. It can learn and forecast waste creation trends and provide timely alerts to the right staff through a firebase cloud messaging system and a dynamic online data dashboard, thanks to an artificial neural network.

Using GIS and data-driven optimisation models, the routeing of collection trucks may be customised and dynamically adjusted using real-time data. As a result, the collection service can be significantly enhanced without an increase in resource requirements. Cotet et al. created a cloud-based automated system for novel garbage collecting services to ensure real-time data transfer. The integration of smart sensors, data, and optimisation algorithms constitutes a smart CPS for the gathering of EOL products in reverse logistics with rising client participation on digital channels, the collecting service may be tailored to specific customer needs [200-201]. This offers a new business model for enhanced policy-making and value proposition, such as pricing-by-service, and for improved stakeholder relations. In addition, the employment of intelligent robots for autonomous trash collection has lately received increased attention during the COVID-19 pandemic as a result of its possible influence on lowering infection risks among healthcare personnel.

3-3- Intelligent sorting and procedure management

Due to the complicated content and quality of end-of-life (EOL) items in reverse flows, sorting has historically been a semiautomated and labor-intensive operation, requiring human employees to physically pick up and separate recyclables. However, the dangerous chemicals and severe working conditions pose major health risks to these employees. Recent advancements in AI and vision-based systems have enabled intelligent robots to recognise and autonomously separate various kinds of recyclables [239-241], which has the potential to revolutionise reverse logistics operations. An intelligent robot-based automated sorting system has been studied for isolating dangerous elements from WEEE. Recent study indicates that the separation accuracy of robot-based smart systems may reach up to 90% for some EOL items, such as aluminium cans and plastic bottles. Ismail et al.created a prototype of small-scale automated sorting bins using smart sensors and material classification technologies to facilitate the collecting of various kinds of end-of-life (EOL) items at the sources, such as the home and workplace.Additionally, Industry 4.0 technology may improve the management of diverse processes and infrastructure. The end-to-end integration of radio-frequency identification (RFID), Bluetooth low energy (BLE), smart sensors, smart containers, and a hybrid gateway in a networked CPS enables real-time information collected from various reverse logistics processes, i.e., returned product identification, classification, local information, and global information, which can be utilised for improved inventory control and environmental management of the entire process [59-60]. The increasing output of infectious garbage during the COVID-19 pandemic presents a reverse logistics problem [11], because a considerable amount of this waste is mixed with conventional waste, particularly in underdeveloped nations. Kumar et al. build an AI-based automated system that offers an integrated solution for more precise separation of COVID-19-related medical waste streams from other waste kinds to facilitate data-driven recycling planning [110].

3-4- Intelligent reuse and recycling

From cloud-based systems to digital twins, Industry 4.0 opens the path for a data-driven smart remanufacturing process [217]. Traditional remanufacturing is hindered by the high degree of unpredictability around the quality, quantity, timing, and locations of returned EOL items, such as WEEE and used automobiles. A product-based digital twin that blends IOT and cloud technologies allows intelligent data collecting and condition monitoring across the whole product life cycle[217]. In addition, users may offer product-related information through several digital channels, such as smartphone applications and websites. On the basis of the generic architecture presented by Wang and Wang [214-218], a customised digital twin may be created for recording the pertinent data of individual items, which will be utilised for improved identification, classification, and sorting in subsequent processing.

Big data analytics may assist enhance the value recovery of end-of-life (EOL) items by providing more precise information on manufacturing schedules and reverse logistics possibilities. Using real-time product information and system data as the dynamic inputs to the optimisation models may boost the efficacy and resource utilisation of remanufacturing via enhanced and more adaptable production planning [240]. In addition, data-driven intelligent disassembly may prevent product damage and increase the quality and predictability of remanufactured items. Additionally, other technologies may aid in enhancing the remanufacturing and recycling processes. For instance, the quality and efficacy of maintenance service and functionality restoration in remanufacturing may be enhanced by providing intuitive step-by-step AR assistance to human operators during product disassembly.In addition, UAVs may aid in the monitoring of the remanufacturing process. Additive manufacturing offers a more adaptable and cost-effective method for restoring the functionality of end-of-life goods and disassembled parts. In a smart remanufacturing process, computer-based simulation may give detailed and graphical insights into system behaviour at the system level. In this context, hybrid simulation approaches, including system dynamics, discrete event simulation, and agent-based modelling, are used to examine the influence of smart technologies and the economic sustainability of remanufacturing [137].

3-5- Intelligent transport and distribution

The efficient sharing of information and resources is one of the most essential characteristics of Industry 4.0, and it allows diverse stakeholders in a reverse logistics system to better use their resources. Utilizing IOT-based intelligent systems has enabled the dynamic optimisation of demand allocation and transport vehicle routein [120-126]. GIS, IOT sensors, 4G/5G devices, RFID, and GPS devices capture real-time vehicle data, which is then analysed to match it with task data from other firms. Finally, assignments and routeing choices are adjusted to maximise the usage of available cars for many assignments from various organisations. With real-time traffic data for dynamic routeing, the system may be further refined to reduce fuel consumption, glasshouse gas (GHG) emissions, and traffic congestion. Gebresenbet et al. propose a web-based information sharing system for the reverse logistics management of agricultural biomass. Through the collection of real-time data from both smart devices and end-users, the demand and supply may be better matched to achieve a high degree of inter-company resource utilisation. Enhanced traceability may aid in reducing product losses and logistical expenses, while simultaneously enhancing market potential and product quality. Moreover, by attaching cameras, smart sensors, and radar equipment to the network of AI-enabled onboard computers, self-driving trucks have shown a significant capacity for autonomous driving [224-225]. In some jobs, intelligent AI has already surpassed human skill, and as autonomous vehicle technology continues to mature, the paradigm of reverse logistics will be radically altered in the near future.

3-6- Smart disposal

The problem of garbage disposal is not only concerned with disposing of waste in the correct location, but also with minimising the amount of waste disposal, safety concerns, and cleanliness. Even if a growing number of end-of-life (EOL) items are being recycled, incinerator facilities and landfills are still the ultimate destinations for non-recyclables in reverse logistics systems, where intelligent robots may replace human employees in tough working circumstances. IOT-enabled intelligent solutions may aid in the monitoring of key performance indicators and the remote control of various processes. Both landfill gas and leachate, a high-density, toxic liquid, have substantial consequences on the ecosystem and must be managed accordingly. A cloud-based IOT system may integrate relevant field data with appropriate mathematical models to examine many essential factors, such as turbidity, suspended particles, and dissolved oxygen, for smart leachate disposal. Moreover, the smart bin is a solution for simple garbage disposal without touching the lid, therefore preventing the transmission of illness, particularly during pandemics [52].

4- An upcoming research agenda

Figure 6 demonstrates the architecture that supports the smart and sustainable transition in Reverse Logistics 4.0 by examining the possible implications of Industry 4.0 technologies on reverse logistics operations. The evolution of smart and sustainable reverse logistics depicts clearly the merger of physical and digital value chains. On the one hand, a physical value chain depicts the interand intra-organizational use and effects of these disruptive technologies. From a technology aspect, a digital value chain evaluates the long-term effects on value-adding and value recovery patterns. The proposed architecture explicitly ties together reverse logistics activities, cyber-physical connection and interaction enabled by Industry 4.0, and technological enablers for the intelligent transformation of collection, sorting and process management, remanufacturing and recycling, transportation and distribution, and waste disposal. Notable is the fact that the targeted sustainability goals are centred on the architecture of smart reverse logistics transformation, which further demonstrates that the ultimate goal of Reverse Logistics 4.0 is not to adopt technology, but rather to improve sustainability through service and operation transformation using technology, as depicted in Figure 5. In this context, Industry 4.0 technologies may give more data, more connection, more intelligence, more flexible automation, and better resource sharing, enabling the enhancement of different reverse logistics operations and processes to better achieve sustainable objectives. In addition, Fig. 6 depicts a mapping between the smart reverse logistics transformation and the appropriate Industry 4.0 enablers based on an examination of documented research and instances in the literature [52].

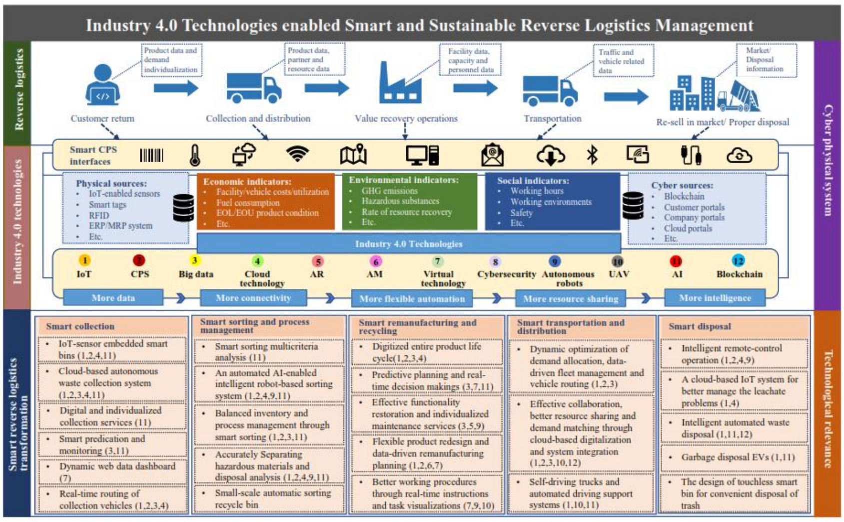

Fig 6- The architecture of the smart reverse logistics system enabled by Industry 4.0

Recent research has focused more on Industry 4.0-enabled smart and sustainable reverse logistics et al. but there are still gaps that need to be filled, such as a lack of comprehension and understanding of Industry 4.0, unclear benefits, and a lack of quantitative approach for performance evaluation[196-199]. Thus, we have suggested four potential study directions:

• Smart and creative reverse logistics services: Reverse Logistics 4.0's paradigm change is mostly driven by service innovation in order to better achieve sustainability objectives. However, the present study focuses mostly on the smart operations of discrete reverse logistics activities and not on service innovation, which inhibits the implementation of Industry 4.0 technologies in the real world owing to the lack of clarity about the advantages to customer. In addition, the role of customers in the change to smart reverse logistics has not been well examined. Even though digital platforms are widely used today for better information sharing between customers and collection companies, such as on the collection schedules of various types of end-of-life (EOL) products and waste, they are primarily unidirectional and customers cannot request individualised collection service based on their specific needs. Thus, research must be conducted to better comprehend how Industry 4.0 technologies can be utilised to effectively and efficiently meet individualised demands in reverse logistics, which opens up a variety of research opportunities, such as demand/data-driven collection service systems, new business models, and pricing strategies for the value proposition through demand individualisation and service diversification. In addition, a cloud-based system can provide a platform for end-users to register the relevant information of returned end-of-life (EOL) products [214-218], but the supporting policies and mechanisms to encourage the customers' active participation in reverse logistics have not been well established. In this regard, future research is encouraged to concentrate on service innovation and smartness, as well as the customers' role and active participation in Reverse Logistics 4.0, so that "service-based individualisation" can be interpreted in a manner that better demonstrates customer value and company benefits. Eventually, it will aid in promoting the intelligent and sustainable transition of Reverse Logistics 4.0.

• Quantitative methods for intelligent and sustainable management of reverse logistics: Industry 4.0-enabled intelligent reverse logistics services will result in a revolution of conventional reverse logistics operations by enhancing connection, intelligence, and autonomy. Thus, new quantitative models or new ways of utilising and integrating existing models are required to address new challenges , such as predictive operational planning with artificial intelligence and real-time data integration, and to better support strategic, tactical, and operational decisions for smart and sustainable reverse logistics management. For instance, the design of a reverse logistics network is one of the most significant strategic designs that may have long-term effects on sustainable performance. The smart transformation in Reverse Logistics 4.0 may drastically alter operations and critical factors within the planning horizon, resulting in a much more complicated initial network architecture. In addition, implementing Industry 4.0 technologies to reduce internal operating costs through digital end-to-end integration is difficult and requires a substantial initial investment [15]. Therefore, a comprehensive analysis is required to comprehend the long-term effects of this smart transformation. In this context, new quantitative models and methodologies are necessary for improved decision support and complete scenario studies of the possible influence of smart reverse logistics transformation on strategic network architecture, which may give decision makers with holistic insights.

- Digital twin of reverse logistics: As depicted in Fig. 6, the combination of the physical world and the cyber world in a smart digital twin is a promising research direction in Reverse Logistics 4.0, where, for instance, AI-enabled data prediction and real-time data collected from both cyber and physical sources can be used collaboratively with mathematical models and computer-based simulation to better predict the key parameters or the parameter distributions for the quantitative decision support models[239-241].The high-quality representation of the reverse logistics system may assist decision-makers in analysing various activities more thoroughly. In addition, the development of bidirectional control and interactions of the intelligent digital twin enables autonomous reverse logistics operations. A smart digital reverse logistics twin necessitates an in-depth methodological integration and a high-level system integration, wherein diverse smart robots and devices, software, data, analytical models, visualisation tools, etc. must be effectively and seamlessly connected and interacted with one another [196-199].In addition, owing to the complexity of the flows and the participation of several stakeholders, the system boundary of the smart transformation must be clearly defined in order to provide a more effective interaction with various reverse logistics participants. In addition, different indicators of sustainability must be assessed using both cyber and physical sources and must be accounted for in quantitative models for decision support. Real-time routeing may be dynamically adjusted to balance economic expenses, truck usage, glasshouse gas emissions, and driver's working time, for instance.
- Human-centeredness and reverse logistics, version 5.0: Even if potential for enhancing sustainability and the circular economy have been addressed, Industry 4.0 is essentially a paradigm change driven by technology. The recently proposed concept of Industry 5.0 has led to a shift in emphasis from technology to human-centricity, resilience, and sustainability in the transition of many sectors [58][87-88], which may lead to new research directions for smart reverse logistics transformation. Industry 4.0 focuses, for instance, on the development of autonomous solutions to replace human labourers. However, Industry 5.0 stresses the synergy between people and technology, where technologies are employed not to replace humans but to assist human employees and provide new employment possibilities [87-88]. In this context, additional study into the human-centric, robust, and sustainable transformation of Reverse Logistics 5.0 is encouraged. Examples of specific topics include the updated sustainability goals in Reverse Logistics 5.0, particularly from the social and environmental perspectives, human-machine collaboration in reverse logistics, the use of augmented reality (AR) and collaborative robots (Cobot) in various operations [160].

5- Conclusion

Today, Industry 4.0 offers new prospects and solutions for combining physical components and data, autonomous technologies, internetand cloud-based connections, data-driven analytics, and model-based analytics in highly digitalized and intelligent reverse logistics systems. However, a systematic framework to drive the paradigm shift of reverse logistics in Industry 4.0 is still lacking. Consequently, this article seeks to contribute to the definition and conceptual development of Reverse Logistics 4.0 by addressing the following three research questions:

- In response to RQ1, the theoretical and practical development of the notion of reverse logistics is compared to the four Industrial Revolutions in human history. Then, Reverse Logistics 4.0 is described in light of the paradigm change brought about by Industry 4.0.
- To address RQ2, a broad conceptual framework for the transformation of smart reverse logistics is suggested, taking into account technical enablers, smart service transformation, smart operation transformation, and sustainability objectives. In addition, the ramifications of implementing Industry 4.0 technologies for smart collection, smart sorting and process management, smart remanufacturing and recycling, smart transportation and distribution, and smart disposal are exhaustively examined.

- To address RQ3, a research agenda with four research areas is presented to illustrate the road map to Reverse Logistics 4.0 through smart and sustainable transformation, and numerous particular subjects are also offered for each research route.

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