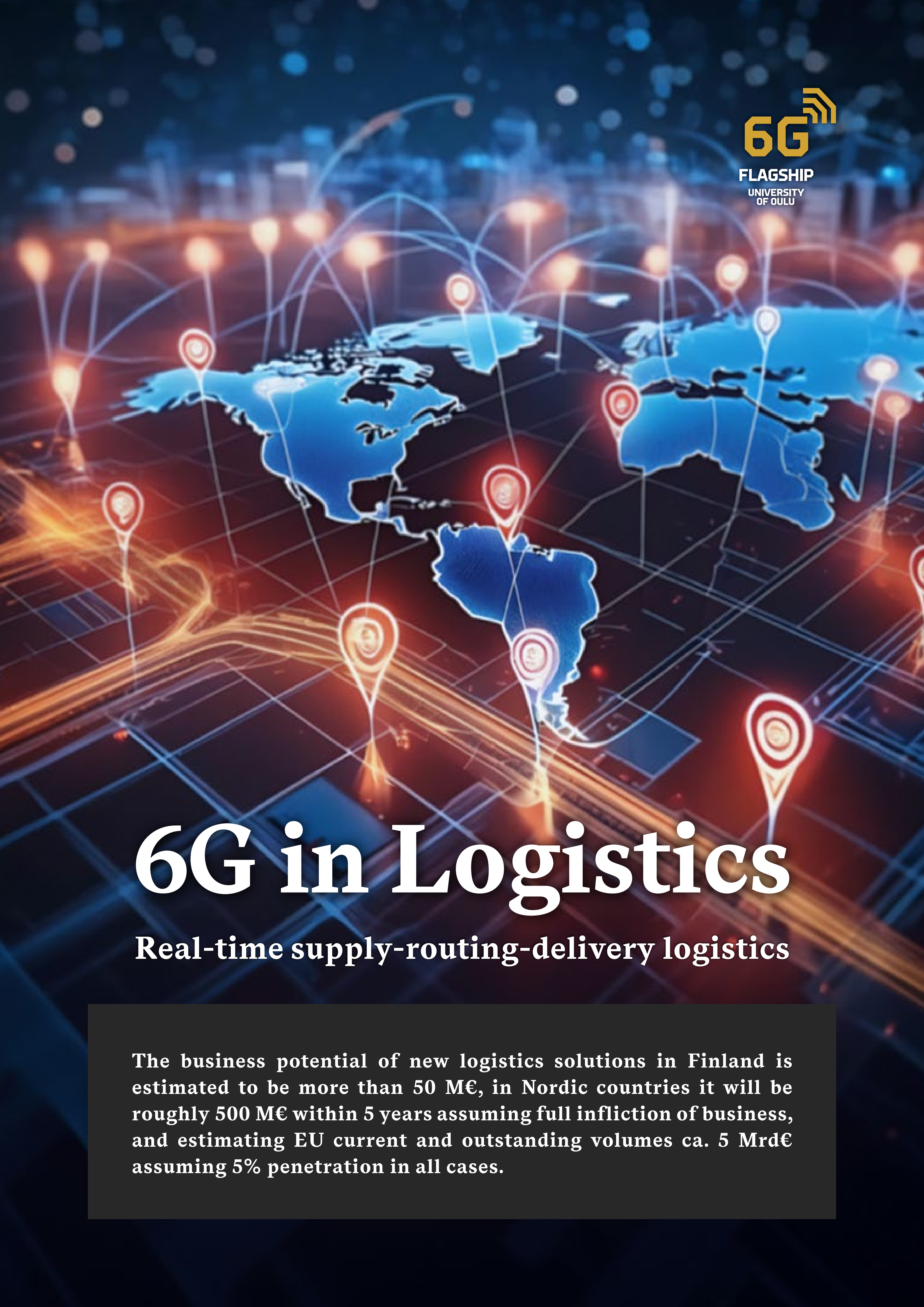

6G in Logistics

Real-time supply-routing-delivery logistics

The business potential of new logistics solutions in Finland is estimated to be more than 50 M€, in Nordic countries it will be roughly 500 M€ within 5 years assuming full infliction of business, and estimating EU current and outstanding volumes ca. 5 Mrd€ assuming 5% penetration in all cases.

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Executive summary

This paper examines the current challenges in logistics and discusses the path and opportunities to 2030, when many new forces are expected to enter the logistics markets. These include, for example, 6G technology capabilities, the EU's package re-use, circular economy, self-sufficiency, and digitalization acts, programs, and directives, as well as the transition to a real-time economy and the rapid adoption of AI. The paper examines these potential areas for innovation, shifts, and opportunities, and proposes adaptable, sustainable, and efficient solutions to some of the identified key challenges and opportunities. The emphasis is on Finnish actors' capabilities to leverage our strengths in capturing these market opportunities, but the scope is global as a logistics business.

Logistics is a broad business that affects almost every company and public enterprise, either directly or indirectly. Logistics has been at the forefront of automation and digitalization for obvious reasons: It is a customer-driven business, and its efficiencies (and shortcomings) are directly visible in operational KPIs. Thus, every company whose operations rely on the efficiency of logistics is expected to spend more money on logistics costs (storage, transportation, labor, and equipment) each year. For example, transportation costs in the United States exceed $1.04 trillion (10.4% of total revenues), whereas total business logistics spending accounted for 8% of the $20.5 trillion US GDP in 2018 [6]. New solutions based on digitalization and 6G aim to reduce this expenditure providing a significant benefit.

Logistics challenges are global, and any company trading internationally must improve the efficiency of its logistics processes. As a result, the technologies, products, and services created through successful solutions will have a high export potential. The preliminary business value of further digitalizing and streamlining logistics services has been estimated to be high, particularly for smart shipments, which have a business potential of more than €50 million over five years nationally. The business value in the Nordic countries is expected to be around €500 million within five years, assuming full implementation. Current and outstanding EU volumes are estimated at around €5 billion, with a 5% market penetration.

Larger business opportunities for Finnish companies may exist in the smart package area: According to the proposed EU regulation, 40% of transport packaging or sales packaging for transport must be reusable by 2030, with the goal of reaching 70% by 2040. This opens up significant opportunities for innovation in ICT companies, material companies (companies that create reusable packaging), and the logistics industry. As a result, the directive will drive up demand for advanced packaging solutions that can withstand multiple use cycles (the EU's target is at least 10) while remaining easily recyclable. The incorporation of 6G technology, sensors, and AI into these reusable packages will enhance their functionality and value. Smart packages equipped with these technologies will enable real-time tracking, condition monitoring, and increased security, thereby improving logistics efficiency and transparency.

The combination of reusability and the 6G ICT technology family will not only meet regulatory requirements, but will also create new business models, service opportunities, and product categories. Companies that innovate in this space will be well-positioned to take the lead in a market that is increasingly concerned with sustainability and technological advancement.

6G technology holds immense potential in revolutionizing logistics by enhancing connectivity, automation, and efficiency. With ultra-fast data transmission speeds, embedded local AI and ultra-low latency, 6G networks can facilitate real-time tracking of goods, enabling precise inventory management and supply chain optimization.

Furthermore, the integration of artificial intelligence and machine learning algorithms in 6G networks can enable predictive analytics, reducing transportation costs, and minimizing delivery times. Overall, 6G has the potential to reshape the logistics industry, making it more agile, responsive, and resilient to future challenges.

Tiivistelmä

Tässä dokumentissa analysoidaan logistiikan nykyisiä haasteita ja mahdollisuuksia vuoteen 2030 mentäessä, jolloin monien teknologioiden, direktiivien ja digitalisaation odotetaan vaikuttavan alaan merkittävästi. Näihin kuuluvat esimerkiksi 6G-teknologian mahdollisuudet, EU:n suunnitelmat pakkausten uudelleenkäytöstä, kiertotaloudesta, omavaraisuudesta ja digitalisaatiosta, sekä siirtyminen kohti reaaliaikataloutta ja tekoälyn hyödyntämistä. Muutos luo potentiaalisia innovaatioalueita ja mahdollisuuksia joiden perusteella dokumentissa ehdotetaan uusia ratkaisuja tunnistettuihin keskeisiin haasteisiin ja mahdollisuuksiin. Painopiste on suomalaisten toimijoiden kyvyssä hyödyntää vahvuuksiamme näiden markkinamahdollisuuksien tuotteistamisessa, pitäen näkökulmana logistiikka-alaa globaalina liiketoimintana.

Logistiikka on laaja ala, joka vaikuttaa lähes jokaiseen yritykseen ja julkiseen organisaatioon joko suoraan tai epäsuorasti. Logistiikka on ollut automaation ja digitalisaation eturintamassa ilmeisistä syistä: Se on asiakaslähtöinen liiketoiminta, ja sen tehokkuus (ja puutteet) näkyvät suoraan operatiivisissa avainmittareissa. Siksi jokaisen yrityksen, jonka toiminta riippuu logistiikan tehokkuudesta, odotetaan käyttävän enemmän rahaa logistiikkakustannuksiin (varastointi, kuljetus, työvoima ja laitteet) vuosittain. Esimerkiksi Yhdysvalloissa kuljetuskustannukset ylittävät 1,04 biljoonaa dollaria (10,4 % kokonaisliikevaihdosta), kun taas yritysten kokonaislogistiikkakulut olivat 8 % Yhdysvaltojen 20,5 biljoonan dollarin BKT:sta vuonna 2018. Digitalisaatioon ja 6G:hen perustuvat uudet ratkaisut pyrkivät vähentämään näitä kuluja tarjoten merkittävää hyötyä.

Logistiikan haasteet ovat globaaleja, ja kaikkien kansainvälisesti kauppaa käyvien yritysten on parannettava logistiikkaprosessiensa tehokkuutta. Tämän seurauksena onnistuneista ratkaisuista syntyneillä teknologioilla, tuotteilla ja palveluilla on korkea vientipotentiaali. Logistiikkapalveluiden digitalisoinnin ja tehostamisen alustava liiketoiminta-arvo on arvioitu korkeaksi, erityisesti älylähetysten osalta, joilla on kansallisesti yli 50 miljoonan euron liiketoimintapotentiaali viiden vuoden aikana. Pohjoismaiden liiketoiminta-arvon odotetaan olevan noin 500 miljoonaa euroa viiden vuoden sisällä. Nykyisten ja tulevien EU:n volyymien arvioidaan olevan noin 5 miljardia euroa, 5 % markkinaosuudella.

Suomalaisille yrityksille voi olla suurempia liiketoimintamahdollisuuksia älypakkausten alueella: Ehdotetun EU-sääntelyn mukaan 40 % kuljetus- tai myyntipakkauksista on oltava uudelleenkäytettäviä vuoteen 2030 mennessä, ja tavoitteena on saavuttaa 70 % vuoteen 2040 mennessä. Tämä avaa merkittäviä innovointimahdollisuuksia ICT-yrityksille, materiaalialan yrityksille (yritykset, jotka luovat uudelleenkäytettäviä pakkauksia) ja logistiikka-alalle. Tämän seurauksena direktiivi lisää kysyntää edistyneille pakkausratkaisuille, jotka kestävät useita käyttökertoja (EU:n tavoite on vähintään 10) ja ovat samalla helposti kierrätettäviä. 6G-teknologian, antureiden ja tekoälyn integrointi näihin uudelleenkäytettäviin pakkauksiin parantaa niiden toiminnallisuutta ja arvoa. Älypakkaukset, jotka on varustettu näillä teknologioilla, mahdollistavat reaaliaikaisen seurannan, kunnonvalvonnan ja parannetun turvallisuuden, mikä parantaa logistiikan tehokkuutta ja läpinäkyvyyttä.

Uudelleenkäytettävyyden ja 6G ICT -teknologiaperheen yhdistelmä ei ainoastaan täytä sääntelyvaatimuksia, vaan luo myös uusia liiketoimintamalleja, palvelumahdollisuuksia ja tuotekategorioita. Yritykset, jotka innovoivat tällä alueella, ovat hyvissä asemissa johtamaan markkinoilla, jotka ovat yhä enemmän huolissaan kestävyydestä ja teknologisesta kehityksestä.

6G-teknologialla on valtava potentiaali mullistaa logistiikka parantamalla yhteyksiä, automaatiota ja tehokkuutta. Ultra-nopeiden tiedonsiirtonopeuksien, paikallisen tekoälyn ja erittäin alhaisen viiveen avulla 6G-verkot mahdollistavat tavaroiden reaaliaikaisen seurannan, tarkan varastonhallinnan ja toimitusketjun optimoinnin.

Lisäksi tekoälyn ja koneoppimisalgoritmien integrointi 6G-verkkoihin voi mahdollistaa ennakoivan analytiikan, vähentää kuljetuskustannuksia ja minimoida toimitusaikoja. Kaiken kaikkiaan 6G:llä on potentiaalia muokata logistiikka-alaa, tehden siitä ketterämmän, reagoivamman ja kestävämmän tulevaisuuden haasteille.

1 Introduction

This paper addresses the interconnection and opportunities of evolving logistic business and latest ICT technologies, such as 6G, AI, sensors and materials.

In this context we lean to the goal of the Finnish 6G Flagship whose aim is to create a data-driven, sustainable future society by 2030 beyond, made possible by ubiquitous, instantaneous wireless and multi-channel connectivity and many technology areas integrating to this vision.

These opportunities are now wakening up many vertical businesses and societal sectors; one of the most important is logistics with its' critical supply-chain process requirements, touching every aspect of modern societies and businesses, as there are more and more concrete research, directives, regulations and standardization advances in oncoming years.

For these, 6G means an opportunity to enter towards "real-time economy". This combined with e.g., latest advances in AI offer lots of new room to innovate and create new products, business models and services.

Logistics as a business entity is one of the first beneficiaries, with important questions like:

1

What does 6G family offer to logistics services, products, processes and applications?

2

What 6G can bring to different parts of logistics, from individual packages to system-level operarations?

3

Where do we need to invest to reach the next level in QoS, resiliency, sustainability and delivery of goods and materials?

4

How do we use 6G technologies to support critical value-chains, security of supply, and create new global business opportunities utilizing 6G roll-outs?

5

What kind of changes in technology, business and people-related issues are expected as a result?

6

Where should we put our R&D efforts to gain optimal benefit and fulfillment of future KPIs?

This white paper examines these questions.

1.1 Global situation

Logistics is a cornerstone of global trade, requiring sophisticated, interconnected processes.

Efficient logistics systems depend on long-term cooperation and partnership across nations and operators. The global trend towards automation and digitalization is reshaping logistics, transitioning from regional specialization to a more integrated global economy. Key drivers include the support of international trade, innovation in economic potentials, robust infrastructure, and the removal of trade barriers through regulatory harmonization. For international trade to run well, it requires a sophisticated system of interconnected technologies and processes. Logistics on a global scale requires the formulation of the development of long-term systems that link the structures of various nations and operators based on division of labor, partnership, and cooperation through contracts, agreements, and common plans supported at the inter- and intra-nation level.

The automation of logistics is a wider trend in the global economy, one that has seen an activity shift from regional specialization to a more diffusely structured worldwide economy. Forming, supervising, and optimizing material flows at the macro-regional economic systems to micro-level are the primary responsibilities of future logistics.

Today's key drivers behind the worldwide expansion of logistics management are:

1. Support of international trade.
2. Innovation in economic potential, commodities, and labor.
3. The international logistics intermediaries (e.g. freight forwarding, localized expert operations management, foreign trade) with a robust global infrastructure.
4. The regulation procedures carried out to remove trade, customs, and transportation restrictions, and in addition directives coming from e.g., EU standing packaging directive [23] and oncoming reusable packaging directives [24].
5. The creation of a standards supporting large number of companies with a broad international partners.
6. The cutting-edge ICT and specialized technologies that form the basis of integration in global-to-local logistics systems. The free flow of funds, products, and data across international borders is facilitated by this.

According to the consulting group Next Move Strategy Consulting, the global connected logistics market is expected to increase in size from 21.4 billion U.S. dollars in 2019 to over 41.5 billion U.S. dollars by 2030.

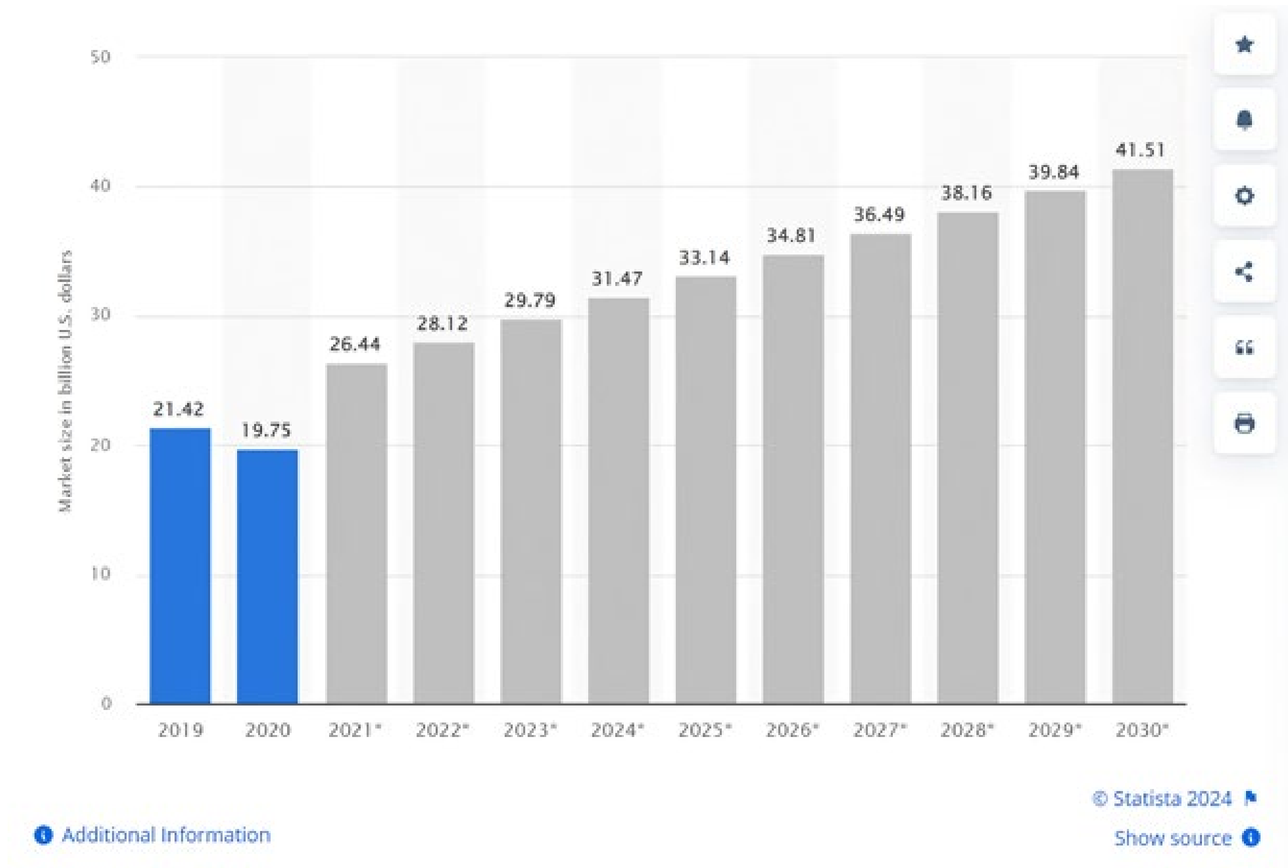


Fig 1. Size of the connected logistics market worldwide in 2019 and 2020, with a forecast for 2021 to 2030. [1]

1.2 Business motivation

6G brings the opportunity to move to "real-time economy". Starting from 2030 this will have a profound effect on supply chains all across the world

6G technology will enter to commercial phase in 2030 and open a profound impact on supply chains worldwide. Advanced logistics companies are shifting towards this with a data-driven mindset, requiring real-time data collection and analysis. The exponential increase in data speeds and reduced latency provided by 6G will enhance network responsiveness, supporting technical and operational transformations. This shift will accelerate and optimize logistics processes from supply chain management to last-mile delivery, creating safer and more reliable logistics systems.

6G, through its intelligent edge with new sensors, AI, and wireless local processing, brings exponentially faster data speeds with reduced latency. This gives rise to a more responsive network that can support technical and operational transformation, while also opening a bouquet of business model development opportunities to be integrated along the logistics supply chain, from processes, supply and logistics centers, all the way down to last mile delivery and dispatch processes. The result of this will be that global and local logistics procedures will be accelerated, augmented, with new set of "Logistics QoS", as well as made safer, robust and more reliable.

6G will enable data-driven, real-time, autonomous logistics

More than a billion new people will join the global middle class by 2030, according to World Data Lab. This growth will strain already-stressed logistics networks. 6G will bring new tools via automation, connectivity, and mobility to minimize logistics demands. [2]

Logistics will become smarter like cities, workplaces, and homes. When the transportation systems, including items to be delivered, is more interconnected via predictive wireless technology, the businesses and consumers will have augmented end-to-end visibility. This would give companies greater visibility into waste and expenses along a supply chain, revealing areas for improvement in sustainability and resilience. Further, the greater visibility ensures consumers know where and when to expect their goods.

Data will eventually supersede other factors as the most essential logistics and transportation currency. 6G telematics services will increase fleet uptime, energy efficiency, and profitability by decreasing unexpected stops, maintenance and operational costs. Telematics' real-time assessments merge with Digital Twin (DT) systems to offer precise improvements to processes over the route planning to enhance operations.

Due to 6G the logistics will transform to value-based business

6G smart logistics will drive value-driven sustainable growth. This value generation will strengthen the supply chain and help reducing emissions or waste.

The 6G value-based vision may benefit many layers in communities. Logistics players employ the knowledge and abilities of their people and their facilities and resources to help causes they favor, from training new data operators to delivering predictive, ultra-precise and resilient logistics routing. What corporations regard as valuable will change, especially in a changing landscape marked by a quest to boost business models and operational credentials. It's no longer just about operating efficiencies; it's also about overall quality of service, decreasing environmental impact, and empowering professionals in logistics business to focus total achieved value. The logistics companies and governments that adopt a full-circle, tech-driven, value-based approach can generate long-term economic advantages, innovation, and job development to benefit the communities they serve.

Preliminary business value has been estimated for at a high level and more specifically for smart shipments, where one reference partner in Finland has verified a business potential of more than 50 M€ for 5 years nationally. We estimate that business value in Nordic countries will be roughly 500 M€ within 5 years assuming full infliction of business and estimating EU current and outstanding volumes ca. 5 Mrd€ assuming 5% penetration in all cases, which is a modest assumption.

Finland's robust technology ecosystem and history of telecommunications innovation position it ideally as a testing ground for 6G applications.

With its highly skilled workforce, advanced research institutions, and supportive government policies, Finland can pilot 6G technologies effectively. This pioneering role not only prepares Finnish companies for global competitiveness but also attracts international partnerships and investments, setting a global benchmark in 6G development and deployment. By focusing on these strategies, Finnish companies can effectively expand their presence and influence in global markets, leveraging their unique strengths and national reputation for innovation.

As the development of 6G network standards progresses, it is crucial for companies involved in creating 6G-based applications to actively participate in the early phases of research and standardization. This proactive engagement is essential because the standardization process will determine the key features translating to business KPIs utilized by the 6G network, which are fundamental to the network's functionality and efficiency.

For industries like logistics, where signal penetration can be a challenge—such as through stacked cargo containers—the selection of appropriate frequency bands becomes even more critical. If the wrong frequency bands are chosen, 6G technology may struggle with signal penetration, leading to inefficiencies and reduced effectiveness of technological solutions in these environments. Therefore, by influencing the standardization discussions and decisions, companies can ensure that the 6G infrastructure supports their specific operational needs and enhances the performance of their applications.

As 6G development is still nascent and resource-intensive, primarily accessible to universities and large telecommunications companies, SMEs face challenges in engaging independently. To prepare effectively for the 6G market, SMEs must join research consortiums. These collaborations provide access to necessary resources and collective expertise, enabling SMEs to contribute to and stay abreast of 6G advancements. By participating in consortiums, SMEs can ensure they are market-ready when 6G networks become widely available, thus safeguarding their competitive edge.

By piloting and testing 6G in logistics solutions in Finland, where the first 6G networks will be deployed, logistics companies can gain a competitive edge. This early adoption allows them to refine technologies and processes, demonstrating reliability and efficiency at scale. With proven 6G-enhanced logistics capabilities, Finnish companies can then market these advanced solutions globally, positioning themselves as leaders in next-generation logistics technology.

Sustainability, resilience and re-cycling are important future themes in logistics

European Commission put forth a proposal to revise the 94/62/EC Packaging and Packaging Waste Directive [cf. 24] in November 2022, which addresses environmental issues associated with packaging and packaging waste. Among other targets, the directive introduces an ambitious reuse target for transport packaging (40% by 2030 and 70% by 2040). This, in turn, introduces an economically viable opportunity to integrate electronics for sensoring and communications to the packaging itself, opening new business opportunities for smart packaging solutions suppliers and Packaging-as-a-Service operators. These new businesses contribute to circular economy by extending the life cycle of packaging materials and reducing waste but also leverages technology to enhance the functionality and value of packaging in global supply chains.

Smart packaging solutions, incorporating sensors and communication technologies, could first be adopted in the logistics of high-value goods, or those requiring stringent regulatory tracking. These innovative packages are particularly suited for items that need verifiable proof of stable environmental conditions, such as consistent temperature and humidity levels. This technology ensures enhanced tracking, safety, and compliance, making it ideal for sensitive products where maintaining specific conditions is crucial for preserving quality and meeting regulatory standards.

2 Key Performance Indicators

Key Performance Indicators (KPIs) for logistics serve as metrics to gauge the effectiveness and efficiency of implementing advancements in logistics. These include key logistics areas such as

1. **Logistics processes**
2. **Operating practices**
3. **Interoperability between and within logistics providers and operators**
4. **Environmental, re-usability and sustainability issues**
5. **Efficiency and profitability**

6G networks, new sensor technologies, Edge and distributed AI and many new technologies have capability to contribute to these targets. By innovating around KPIs, we can introduce new solutions to 1) automation, 2) transparency and 3) real timeliness that translate directly to many critical KPIs within the logistics operations.

By monitoring these KPIs, businesses can measure the tangible benefits of adopting 6G and ICT integration technologies in logistics, identify areas for improvement, and optimize their processes for greater efficiency and competitiveness. Table 1 presents a key set of next generation logistics KPIs, how they can be measured and, what value they provide when achieved.

Table 1. Core KPIs for 6G in Logistics.

Focus area	Main KPI	Sub-KPIs	Measurement Method	Value if Achieved
System Level	Efficiency in system integration	· Integration time reduction · Compatibility with existing solutions	Time tracking, compatibility analysis	Improved system performance, reduced implementation costs
Smart Objects	Object tracking accuracy and accessibility	· Accuracy in location tracking · Reduction in misplacement incidents · Accessibility	Accuracy (% / meter), incident rate tracking	Enhanced object security, reduced losses, faster rerouting, new customer interface
Intelligent Routing	Reduction in delivery times	· Improvement in route optimization · Decrease in delivery delays	Time tracking, delay rate analysis	Increased customer satisfaction, cost savings
Consolidated Sorting	Sorting efficiency	· Reduction in sorting errors · Improvement in sorting speed	Error rate tracking, time measurement	Enhanced operational efficiency, reduced error costs
Real-Time Ledger Management	Data integrity, access speed, and openness	· Reduction in data discrepancies · Speed of data retrieval, availability, and processing · Transparency of information	Data accuracy checks, processing time analysis, and collaboration rate	Improved tracking, better decision-making capability, enhanced flexibility in logistic' steps, and foster collaboration among stakeholders
On-Site Robust Connectivity	Connectivity reliability and coverage	· Reduction in connectivity downtime · Increase in coverage area	Downtime tracking, coverage analysis	Enhanced network reliability, improved operational range

3 Technological solutions

In order to confront the key KPI targets towards 2030, i.e., raising the level of 1) automation, advancing interoperability between operators; 2) transparency, utilizing the novel technical capabilities coming from 6G specification; and AI advances leading to 3) real timeliness, which with 4) new regulation coming from e.g., EU forces industries to develop more robust packages and processes with inbuild environmental targets.

The targets 1) - 4) create many challenges, but also future potential for new business for companies operating in various side of logistics. These include:

1. Packaging business (in Finland for example RePack, Posti, Wulf, Pakkaus Öhman, Lyreco, Verkkokauppa.com),
2. High tech ICT providers and hosters (in Finland for example Nokia, telecom operators),
3. Field operators (in Finland for example Posti), and
4. Number of other adjacent entities operating in logistics ecosystems in Finland and throughout the world (for example Posti, Postnord, DHL, UPS, DP/Schenker, Amazon, and for packaging and smart package targets many ICT companies and materials companies to utilize Finnish strengths).

To make logistics operational areas and eventually the integrated logistics systems able to benefit from 6G and other key ICT technologies, we need to address several existing problem domains and then proceed to develop an integrated 6G enabled logistic systems, product opportunities and solutions.

1. System level

To find and apply the appropriate solutions to logistics challenges, a thorough exploration of the problem domain is required. Several promising building blocks have been examined, each of which adds new functionality and improves performance to the logistic chain, processes, and KPI targets. The ability to bring proactivity to asset flow management and, consequently, critical deviation management is a key expected enhancement. The monetary value is in providing better support for the agreed-upon (promised) level of service. The logistic chain as a whole contains a number of critical data collection points. The system level analysis defines a framework for collecting, managing, and analyzing logistics chain data, or data flow.

Managing and utilizing this data for asset flow optimization and meeting promised service levels on a global scale will result in transportation cost and resource savings.

2. 6G smart objects

– how dumb packets are transformed to smart packages and shipments

The 6G smart objects research area focuses on tracking shipments and developing a transformation path from "dumb" packets to "smart" packets as envisioned in the 6G era. Currently, shipment tracking solutions (Track&Trace) in the logistics industry rely primarily on single barcodes (IDs) or smart tags (RFIDs) in manual shipment documents. Electronic advance information (EDI) has been obtained from these, but transaction data is collected manually or through sorting machine camera tunnels.

Current solutions also do not allow the sender or recipient to transfer their own transactions to shared use. The current frequency ranges are relatively low, making it difficult to integrate smart tags into objects and use large numbers of tags in a single object, which would also benefit the tag reading event. Because older technology does not allow for automatic shipment tracking in centers and terminals, some shipments may go unnoticed, resulting in a failure to deliver on the service level promised to customers. Furthermore, EU directives on packaging and packaging waste reduction mandate actions to achieve the EU's environmental goals [24].

This is a multibillion euro problem globally each year, creating a significant business opportunity for 6G adopting technology companies.

3. Edge-AI-based Intelligent routing

– how 6G helps to avoid mis-shipments

A mis-shipment occurs when an incorrect item or number of items is sent to a customer, the shipment is lost en route, or the customer does not receive their shipment on time. Misshipments are common, but they can have a significant negative impact on a logistics company's profit and loss statement and customer satisfaction. Modern warehousing solution providers promise to deliver shipments to the correct locations on time.

Continuous losses, such as shipments sent to the wrong location or production deviations that necessitate proactive reporting notification and corrective re-routing or re-sending, are easily detectable. Such issues typically arise when the warehousing system fails to recognize the shipments' routing data correctly, or when the shipments are placed in the incorrect transport unit despite the system's instructions.

This results in large amounts of incorrectly placed shipments annually, whose business (loss) value is around 10% of annual traffic. [3]

4. Machine learning for consolidated sorting

- how 6G edge AI helps to combine optimal shipments

The challenge of consolidation, in which many shipments that are being sent to the same recipient and are being picked up and combined into one cargo, is one that has not yet been solved. This results in delays, mis-shipments, shipments of the same order arriving at different times, and additional expenses imposed by re-routing, send-back latencies, and increased expenses for the logistics operator and receiver. Consolidation of shipments saves time, cost and improves end-to-end efficiency of logistics operators' capability.

The estimated savings, and leading to e.g. better end-customer/supplier satisfaction, in global and even national scale is large; logistics and delivery companies can save up to 10-15% of their annual spending if we can optimize the cargo capacities on each delivery routes. This mounts up to billions of euros worth of business opportunity globally in YoY opex.

Multi-client fulfillment drives savings of 7-9% vs dedicated fulfillment.-client fulfillment drives savings of 7-9% vs dedicated fulfillment.

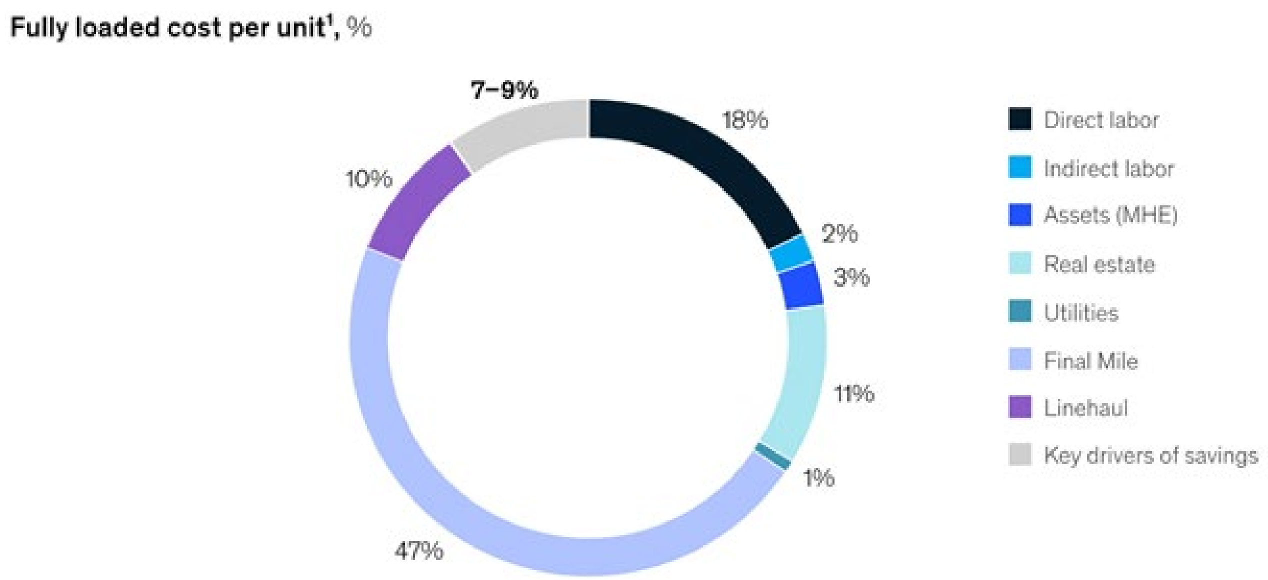


Fig 2. Impact of consolidated sorting, around 90 percent of logistics experts believe that e-fulfillment currently leads to profits of around 5 to 10 percent. [4]

5. Real-time ledger management for tracking

– how 6G edge is combined with blockchain on system level

There are currently no commercially viable, cost-effective, or functional solutions for monitoring and tracking end-to-end transportation units. Current solutions allow for manual scanning of barcodes or ID tags, but they lack digital signatures and real-time ledger support. As a result, each operator has their own solution, which is only interoperable through API integration via proprietary systems. Due to manual tracking, the datapoints collected from shipments and transport units are suboptimal, with low sampling frequency (and human or sorting error).

This all has a significant impact on end-to-end logistics flexibility and reliability, from the sender to the end customer. Blockchain combined with 6G will create a distributed interoperable ledger capable of recording all transactions and updating records in near-real time. Using this data, operators can streamline the delivery process by establishing more direct routes, optimizing shipments, and eliminating unnecessary processes.

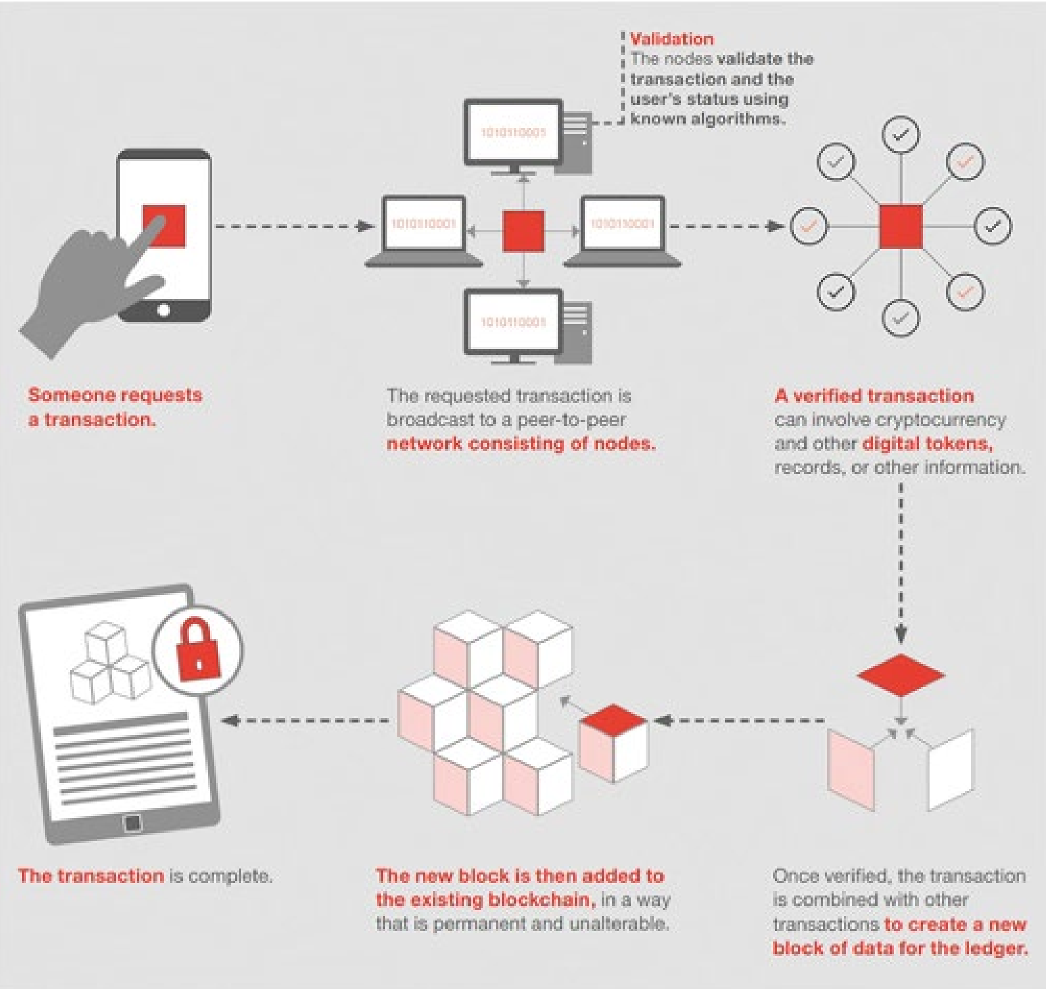


Fig 3. Example of generating blockchain-based ledger for logistic shipments. [5]

Thus, the solution the industry needs should be based on real-time ledger technology, made possible by 6G's real-time tracking capability and smart edge (local) computing combined with ledger management systems that are data-based and use robust untamperable data associated to logistics routing processes.

The business upside opportunity for real-time, operator independent and distributed ledger management system is obviously global with estimated very high business value, the sizing is still being analyzed for 5G era, for 6G we need to analyze this further.

6. On-site robust connectivity

– 6G in future shipment machines, surrounding infra and processes

In current shipment machines, the data transfer option is limited to the image and voice ratio, in which case 5G Advanced and 6G APT machines would enable better remote customer service and monitoring. The e-commerce and logistics business are focused on ICT and production technology, which requires functional and scalable wireless data transfer solutions.

The capacity requirement increases every year and new production technical solutions require fast and high-performance data transmission capacity, which are currently based on either LAN, WiFi or 4G solutions. Operators have often encountered problems with WiFi and 4G, such as the QoS, coverage, and expansion needs of the wired LAN network. A LAN always requires functional cabling and routing, which are not always possible to expand even with slow additional cabling work. Robotics, AGVs, machine vision, machine learning & AI will require rapidly scalable and reliable wireless data transmission, which will be made possible in stages by 5G Advanced and 6G.

Regarding the wireless network, the places of use are e.g. sorting centers, distribution and transport terminals and warehouses. 6G will bring very high-speed network, new type of coverage, ease of expansion and much needed real-time properties to facilitate the previously mentioned new capabilities for logistic operators.

The market for these kind of "core 6G wireless" solutions is global, and needed on the automation strategies by all companies in this business. This renders large global business opportunities to various ICT companies from technology to operations (micro-operators to macro, or current telecom companies).

All of the previous problems and opportunities are global, so there are customers for future solutions from both domestic and foreign e-commerce logistics operators. The manufacturing industry also has logistics, which needs the most efficient solutions, which, in addition to improving cost efficiency, needs a wireless data transmission network that increases proactivity.

The 6G in Logistics white paper will analyze key pressure points surfaced within end-to-end delivery processes, several focused areas and eventually systemic changes needed to take the new technology opportunities to use:

1. System level:

Mapping the challenges and already existing solutions that can be utilized.

2. Smart shipments:

6G enablers relevant for improving the tracking of shipments beyond barcodes and dumb tags. Further, oncoming re-use requirements from EU opens new opportunities to develop high-tech package technologies with integrated ICT and 6G capabilities.

3. Intelligent routing:

Utilization of 6G edge capabilities to streamline routing and delivery processes.

4. Consolidated sorting:

Using better digital identities, logistics directives and optimal shipment fulfillment, creating solution potentials to develop new sorting methods via 6G enabled edge computing, AI and IoT.

5. Real-time ledger management:

Identifying and analyzing datapoints, creating systemic approach and analysis of shipment processes and turning the data to ledger compliant service model using e.g. blockchain technology.

6. On-site robust connectivity:

Addressing next generation connectivity needs on-site and through the logistics route, analyzing dark spots and connectivity coverage to develop architecture approach to adopt 6G wireless access.

4 Potential Opportunities for Growth - Research Areas

4.1 System level

The current problems (and opportunities) in logistics described in this document have multiple interconnected building blocks, all of which provide completely novel functionalities and performance enhancements to the logistic chain and necessitate a number of new solutions to enable real-time information management by logistic processes.

The building blocks, or new technological opportunities, are highlighted in the left column of Figure 4 (below), with the corresponding legacy systems and solutions in the right. The undeniable fact is that any new technology or solution must be compatible with the legacy system. This necessitates an extremely cautious approach to possible implementations. Limited-scale Proof-of-Concepts and experimentations are required prior to commercial adoption.

The interactions of smart shipments and packages (objects), intelligent shipment routing and consolidated sorting solutions, and blockchain-based management, as well as their cumulative effects across the entire chain, must be carefully addressed in order to provide real benefits to overall system performance.

Furthermore, a systematic higher-level view of the logistics chain is critical for determining the overall readiness and completeness of the process. This research area identifies appropriate higher-level approaches to developing such a tool.

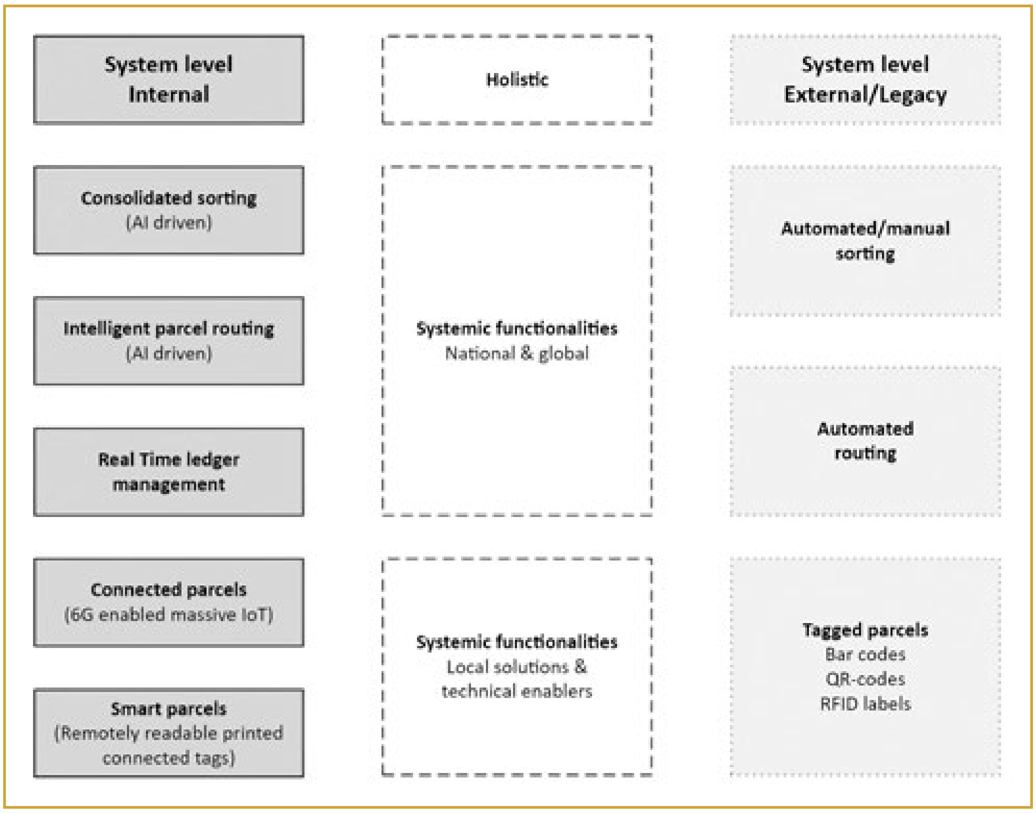


Fig 4. Research topics mapped to system level view.

4.1.1 Digital Twin approach

The logistic chain will form a non-linear and multidimensional problem space which cannot be managed with analytic means or tested in real-time/real-life. Instead, most promising approaches for higher level control and system analysis are based on system level modeling tools, such as modern digital twin-based approaches. Such a model must include only the most relevant system elements and parameters and the dynamic interactions between elements. Moreover, the DT model should be designed scalable by modular design [7].

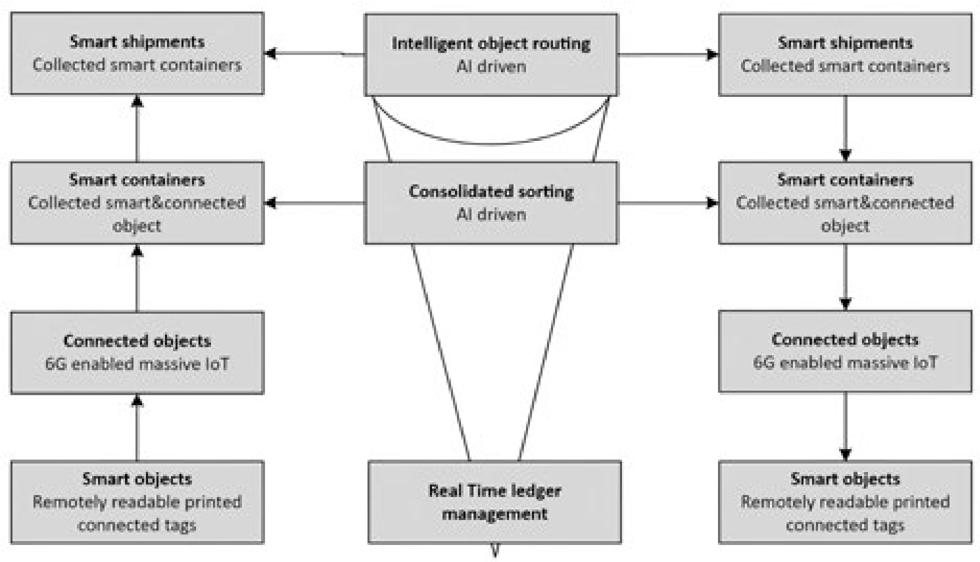
Modeling of a massively complex system including statistical models of material/shipment flows, connectivity model supporting hundreds or even thousands of simultaneous connections and finally the (AI based) optimizable routing and sorting functionalities is a daunting task. The modeling work itself would require an extensive platform to support the multiple features.

Key elements in interactive DT are the smart shipments, including a collection of smart containers which in turn include the smart objects with (printable) active IoT tags allowing them to be identified, located and tracked at any time anywhere within the reach of the supporting wireless 6G network (see Figure 5 below).

DT must include a user interface to follow/monitor the shipment flows in a certain facility and, if needed, zoom in to selected locations and even single out shipments. Obviously, the on-site connectivity is critical for DT & PT (Physical Twin) synchronization.

This allows every single shipment to be tracked in real-time at any time.

Fig 5. DT elements at the system level. Single (smart) objects are connected, then sorted to (smart) containers, then routed to (smart) shipments. At the receiving the process is reversed. All the time the ledger documents and keeps track of events and objects.



Well synchronized DT with suitable UI opens several possibilities to monitor and manage the shipment flows. Most importantly, various AI based solutions can be implemented to the DT to provide optimization to shipment routing and sorting in near real time.

AI based predictive solution (Intelligent DT) [8] can even notice possible emerging problems and provide the solution proactively. In essence, DT includes the whole timeline of events of each shipment. This makes the DT a perfect log for reviewing the process in detail.

4.1.2 Shipment flow approach

A model of the operation of the US Postal Service has been presented in [9] (See Figure 6 below).

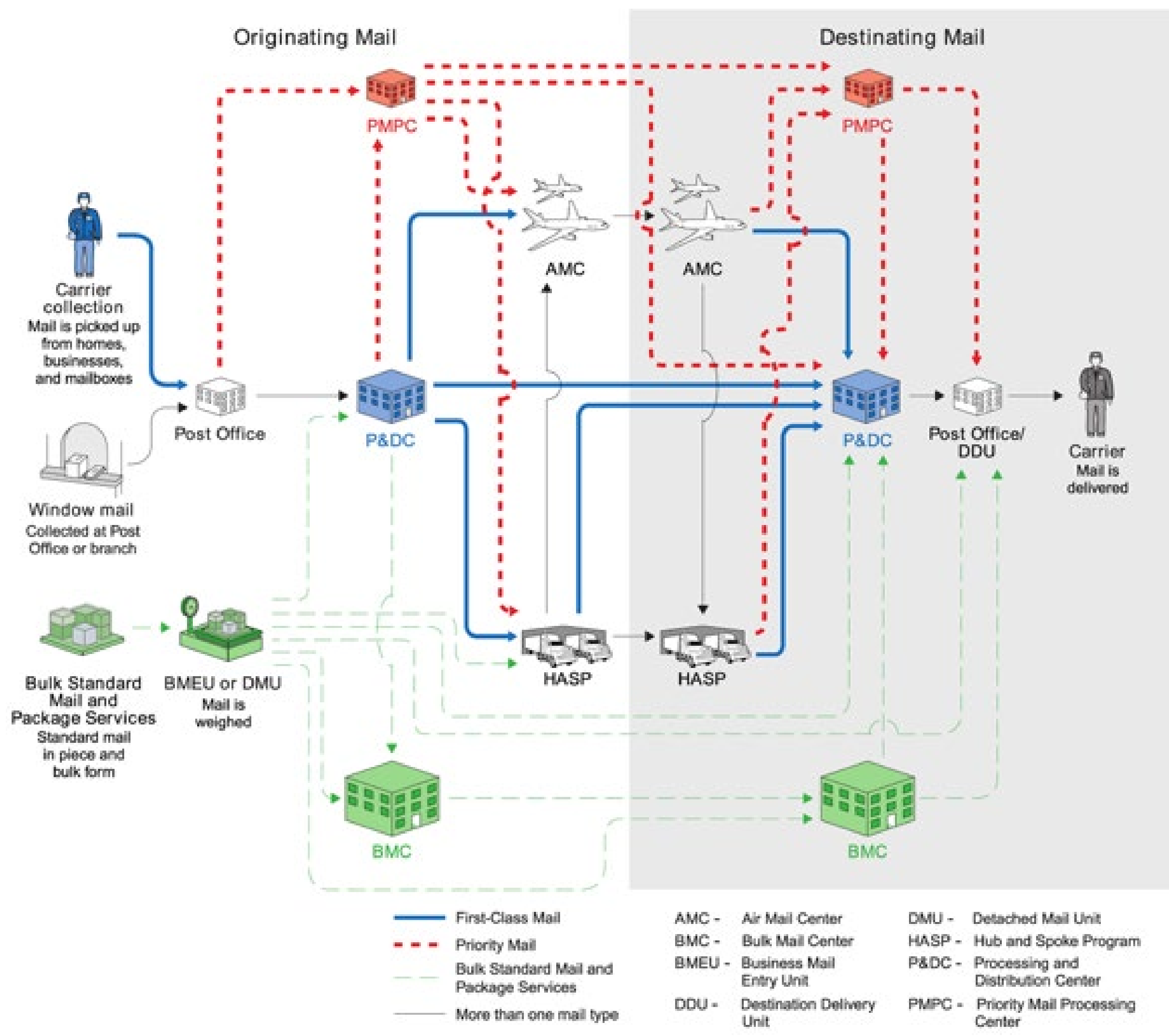


Fig 6. Model of US Postal service [9].

The logistic service should be presented with process that run flows, and the points at which data is entering the flow (for example, data in), the points at which data is being used (for example, data out), and the processing that is taking place in and between these points should be identified.

Flows should be well defined and managed by automated processes. The definition, purpose and attachement to core process flow(s) is also necessary. It is possible to draw parallels between the proposal that we have available to us and the one that we are currently studying here.

The following two simplified illustrations, which represent the Originating Postal Center and the Destination Postal Center, respectively, have been drafted as a result of the preliminary analysis. These are based on current real operations in logistics:

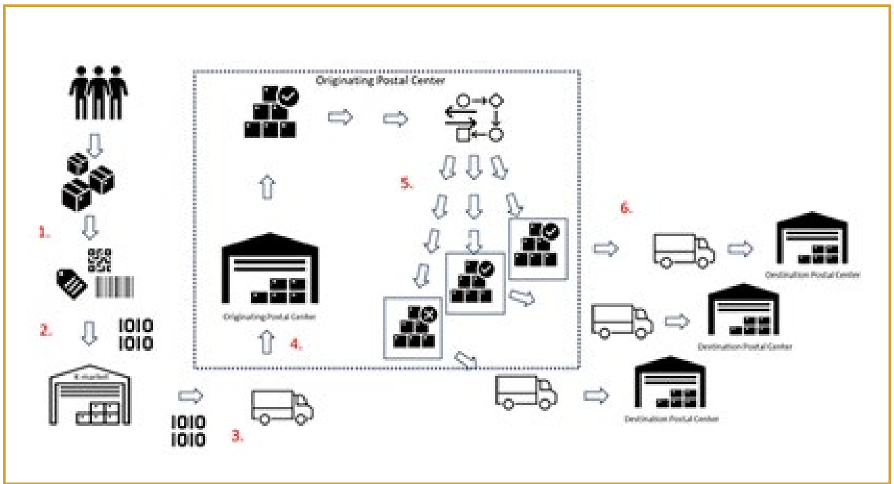


Fig 7. Schematic view of Originating Postal Center.

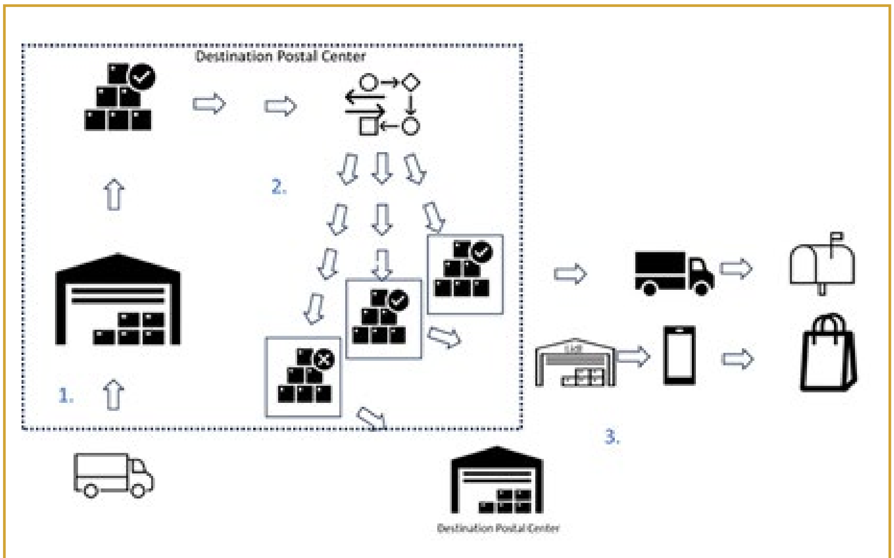


Fig 8. Schematic view of Destination Postal Center.

Note that similar shipment flow diagrams can be applied to any logistic chain, and therefore the main logic behind the approach can be applied generally.

The numbers indicated in the illustrations (1-6 and 1-3, respectively) give some **examples** of the points/ locations, where the data is added and/or used and processed.

The following tables 2 and 3 (below) provide **tentative** explanations for each entry point. By identifying the data entry/exit points and the data processing instances, we may gain better understanding where the novel features provided by WP1-5 are best implemented.

Table 2: Originating Postal Center (SA = Sender Address, RA = Receive Address, SL = Service Level selection)

	Data in	Data out	Processing
1	SA, RA, SL, bar/QR code; addresses	-	Shipment tagging by customer
2	-	RA, SL, physical dimensions, shipment count / originating site	Initial sorting at origin
3	Next handling/sorting site	-	Routing to logistic center
4	Handling location, e.g. conveyor in site	Number of shipments / containers arriving	Unloading to logistics
5	Selected container ID	RA, SL, delivery method: to address, to pick-up, to next handling site	Sorting inside logistic center
6	Shipment/transportation ID, Expected Time of Delivery (ETD)	Pick-up time	Delivery to customer

Table 3: Destination Postal Center (SA = Sender Address, RA = Receive Address, SL = Service Level selection)

	Data in	Data out	Processing
1	Time stamp	SA, RA	Delivery to destination logistics center
2	Delivery method, time slot and location	-	Information sent to receiver
3		Pick-up time, SL estimate	Pick-up by receiver

4.1.3 Goals and KPIs for System level

By identifying the key data in/out/processing points of the shipment flows, it will be possible to integrate the proposed novel 6G related enabling technologies (smart shipments and on-site connectivity) as well as the intelligent routing, consolidated sorting, ledger management process to the logistic chain.

The following table 4 summarizes the main advantages of the 6G technologies in logistics.

Table 4. The main advantages of the 6G technologies in logistics.

6G technology	Possible applications in logistic
Smart shipments	On-site live tracking of shipments, improved tracking precision
Robust connectivity	Real-time information flow between the process key data points and management processes
Intelligent routing	Pre-emptive error detection, on-line rerouting
Consolidated sorting	Real-time data assisted receiver level sorting, real-time changes
Real-time ledger management	Operator independent data management and sharing

Integrated and coherent system level view of the logistic process will enable better assessment of the combined improvement brought by the applied 6G technologies. Each technology building block can be shown to bring their own advantages (see the relevant KPIs listed for each building block), but the combined effect may remain unclear without a holistic approach to assessment. Proposed KPIs need to reflect the overall system performance compared to the state and performance before 6G-technology implementation. Therefore, it is important to find indicators for which i) data reflecting the existing logistic system is available (both real-time and history data), ii) the same data will be available after technology improvements, iii) overall logistic system improvements should be reflected.

Proposed KPIs for system level view are listed in the table 5 below.

Table 5. KPIs for system level.

Main KPI	Sub-KPIs	Measurement Method	Value if Achieved
Shipment delivery delay	1) Total delivery time 2) Delivery time deviation from promised Service Level	Statistics on the deliveries should be available.	- Assessment of improvement by 6G - Indication of possible systematic locations/times where problems remain
Shipment errors	1) Number of lost shipments 2) Number of delayed shipments 3) Number of erroneous shipments	Percentages of shipment success statistics should be available	- Assessment of improvement by 6G - Indication of possible systematic locations/times where problems remain
Customer satisfaction	1) Private customers 2) Business customers 3) Logistic partners (e.g. delivery partners)	Questionaries reflecting service satisfaction.	- Indicates the perceived service satisfaction in general - Enables to pin-point remaining flaws in logistic chain.
Environmental	1) CO2 emissions 2) Fuel consumption/driven miles/km	Same method as used today to assess the CO2 emission level. Kms driven/successful shipment	Important factors in environmental efficiency

4.2 Smart shipments

The primary challenge within the logistics sector is evolving shipment tracking from traditional methods to intelligent systems, as anticipated with the progression towards 6G communications. The prevalent Track & Trace systems are mainly dependent on single barcodes or RFID tags on manual shipment documents. Although this method allows for some electronic advance information (EDI) capture, the transaction data collection is largely manual or relies on optical systems within sorting machines.

The inadequacy of current systems is evident in their lack of support for the seamless transfer of transactional information between the sender and recipient for collective use. This limitation is particularly problematic in distribution centers and terminals, where the absence of autonomous tracking technologies leads to shipments being unaccounted for, thus compromising the service level promised to customers.

To address these shortcomings and prepare for the 6G era, a new approach is proposed. For cost-effective and simplified applications, the implementation of low-cost RFID tags could facilitate basic data storage for enhanced tracking capabilities. These tags could be integrated with sensors to measure parameters like temperature or signal strength, thereby increasing the shipment's intelligence. Standard, and future re-usable packaging materials and structures (EU packaging directive) might also be integrated of embedded with smart tags, potentially with ICT modules or fractal patterned paper, which could significantly improve the precision of tracking.

On the communication and sensing front, there is a clear intent for adopting high-frequency and narrower beam technologies. Higher frequency would also enable smaller size for single tag and opens a way to multiply number of smart tags used in one object. Furthermore, narrower beams would scan physical rooms with high intensity scans enabling higher tracking probability and location accuracy. Such advancements would not only enhance communication and sensing capabilities but also ensure better tracking and tracing of objects, even those without tags.

In the realm of other features, piezoelectric energy harvesters present a cost-effective solution. They capitalize on energy from motion during transit to maintain continuous tag operation. Moreover, traditional labels with QR codes offer a solution for static information display, enhancing data retrieval without the need for real-time updates.

For advanced and high-performance applications, the deployment of tags with high storage capacity and robust communication modules is crucial. These tags would need to withstand prolonged usage and harsh conditions. Furthermore, the introduction of smart materials into packaging that can adapt to environmental changes, be re-used many times, and even self-heal, provides a leap in packaging intelligence. Such materials could alert users to potential compromises, enhancing the security and integrity of shipments.

The suite of other features for these high-end applications includes sophisticated energy harvesters with advanced energy management systems that support sensor operation and data processing. Multimodal communication interfaces are anticipated to integrate various communication standards for enhanced data transfer and global connectivity. Finally, dynamic displays like electronic paper displays for real-time information updates could provide solar-powered operation, ensuring long-term maintenance-free performance.

Tables 6 and 7 represent smart shipment parameters and shipment categorizations.

Table 6: Smart shipment parameters

Item	Operation	Business	Development
Read system	Optical, barcode, RFID, QR code, BT, Wifi, cellular	Post, item tracking, outdoor, indoor, office, truck, ship, airplane, nature	Information should to be received in the same place, high frequency enables higher tracking accuracy
System Integration	Separate systems vs combined information	Crowd sourcing possible	
Open database	Systems` information in same database, open data	Common interest through commercial benefit (money)	Market place missing
Sensor technology	Temperature, shock, moisture	Sensitive item tracking	Slow development, pricing from 10c to 20€
Memory	Data storage, re-writing	Continuous monitoring, re-use with another operator	Market changes between w/wo memory vs pricing
Energy harvesting	High energy resources	Continuous monitoring, read range and quality	Fast development on-going, light, temperature, vibration mechanisms
Multiple tags integrated in package	Structural electronics is trending	Cheap sensors multiplied	Current trend in electronic development
Communication and sensing	Under research, systems integrated	Tracking without tags, use common radio network	Key 6G field enabler for high tracking and location accuracy
Narrow radio beams	Under research, location accuracy	Location accuracy improvement	Key 6G field enabler for high tracking and location accuracy
Electronic paper	Direct user interface	Special items	Sustainable feature
Advanced packages, self-healing	Life-time improved	Green packaging materials	Material development supporting idea

Table 7. Shipment categorization and special functions

Basic Embedded Radio Tags	Standard Packaging Materials with Embedded Tags	Communication and Sensing	Optica l sensing / radio ID tracking
Low-cost RFID tags, limited data storage for tracking	Conventional packaging materials with smart tags	Focus on higher frequency and narrower beams for improved tracking probability, communication and sensing capabilities	Location relationship
Sensors: temperature or signal strength	Fractal patterned paper with many chips	For tag tracking or object (without tag) tracking	Optical marking
Global ID	Several tags (copies) in same shipment	*Using different systems to locate shipment /camera, radio, gps, etc.	*visual / non-visual tracking *thermal camera
	Exploring new materials for packaging that can adapt to environmental changes or signal tampering attempts, potentially integrated with conductive inks or smart polymers	How accurate, where moving, how fast moving (various stakeholders)	

4.2.1 Basic Tag Category

Embedded basic radio tags offer a cost-effective solution as they contain RFID tags with limited data storage, ideal for (limited) tracking purposes. These tags come with sensors that can measure temperature or signal strength and provide basic feedback about the environment. In addition, standard packaging materials can be improved with embedded smart tags. This includes fractal patterned paper integrated into numerous chips and the inclusion of multiple tag copies in the same package to improve trace redundancy.

The communication and detection side focuses on utilizing higher frequencies and narrower beams, which significantly improves both communication and detection capabilities. This technique is not limited to the tracking of marked objects but can also extend to the tracking of unmarked objects. In addition, optical identification and radio ID tracking are used to determine the location relationship, whereby optical marking provides another layer of target identification.

Other noteworthy features include the use of cost-effective piezoelectric materials designed to harvest energy from movement during transport. This energy supports important identification functions without the need for additional power sources. In addition, static display technologies, such as traditional QR-coded labels, provide static information that does not require real-time update capabilities.

4.2.2 Advanced Tag Category

Advanced embedded tags are designed to last, with high storage capacity, multi-functional sensors and rugged communication modules, making them suitable for long-term use in harsh environments. The packaging is sensitive and adaptive, using smart materials that change their properties to protect or signal changes in the environment.

Self-healing materials in packaging can repair minor damage or alert users to potential compromises, improving the integrity of the products in the packaging. Communication and detection technologies have also advanced, introducing higher frequencies and narrower beams to improve communication and accurate detection.

Other features include advanced energy harvesters, which are part of an advanced energy management system that powers the sensors and data processing. These harvesters can collect multimodal energy and ensure continuous power supply. Multimodal communication interfaces include different communication standards, which facilitates global connectivity and fast data transfer.

The inclusion of MIMO technology improves tracking accuracy and reliability. Dynamic displays, like electronic paper displays, provide real-time information updates and are often combined with solar-powered features to allow for long-term autonomous operation.

4.2.3 KPIs for Smart Shipments

Table 8 below presents the main KPIs for smart shipments as we as the expected values if achieved.

KPI Description	Measurement Method	Relevance	Expected Value if Achieved
Object tracking accuracy	Location accuracy in meters (m)	The accuracy and performance of the system improve when the location of the shipment is known in real time	Delivery is faster, more accurate and saves energy and resources
Object tracking frequency	Time scale for object tracking	Object tracking frequency varies by system location. Distribution centers need real-time tracking for efficient inventory management. Trucks require less frequent updates, tailored to their routes and schedules. Near the end-user, real-time tracking improves customer satisfaction by providing timely delivery updates.	Effective tracking frequency ensures smooth operations at distribution centers and minimizes delays. For trucks, it optimizes communication and route efficiency. Near the end-user, it enhances the service experience by keeping customers informed about their deliveries.
Object accessibility	Percentage of objects with open access / rewriting (%)	Objects are a multipurpose interface that can be reconfigured by operators and customers	Object information can be reused, which makes it an inexpensive and easily accessible function for the user

4.3 Intelligent routing

Current warehousing management service solutions can track the shipments, but the systems still have many development areas for more efficient and reliable operation.

An error happening in one part of the logistics chain can have a domino effect in the whole system's operation. It would be very beneficial to be able to model pre-emptively any possible errors, and make decisions in real-time on-the-fly in a case of mis-shipment.

This research area studied the possibilities of modeling the shipments' routes as digital twins to enable data-driven mis-shipment prevention and dynamic correction of routing.

1. Identify the need for any new features for the shipments and their environment on-route. Through this analysis, enhancement of the current environments with edge-based infrastructure and analytics can be suggested.
2. Design of an intelligent sniffer (SW agent) that can be migrated with the shipment and/or within the edge infrastructure to detect any problems while on-route. A study of the migration of data and knowledge in microservices between the smart shipments and their environment. Also, strategies for offloading services between actors and infrastructure are designed.
3. Study of on-the-fly re-routing solutions and their implementation. The solutions are co-designed with other research areas to match smart shipment properties as well as overall optimization and ensure trust.

Figure 9 provides an overview of the proposed solution. Sensor tags (e.g., RFID) on the objects and across the sorting and routing infrastructure provide data on the current status of shipments as well as that of the environment, with intelligent sniffers deployed on object cages, delivery trucks and the sorting infrastructure enriching that data with current as well as predicted location and future status. The digital twin of the intelligent routing receives the data and predictions and provides a real-time predictive view of entire routes and the whole system.

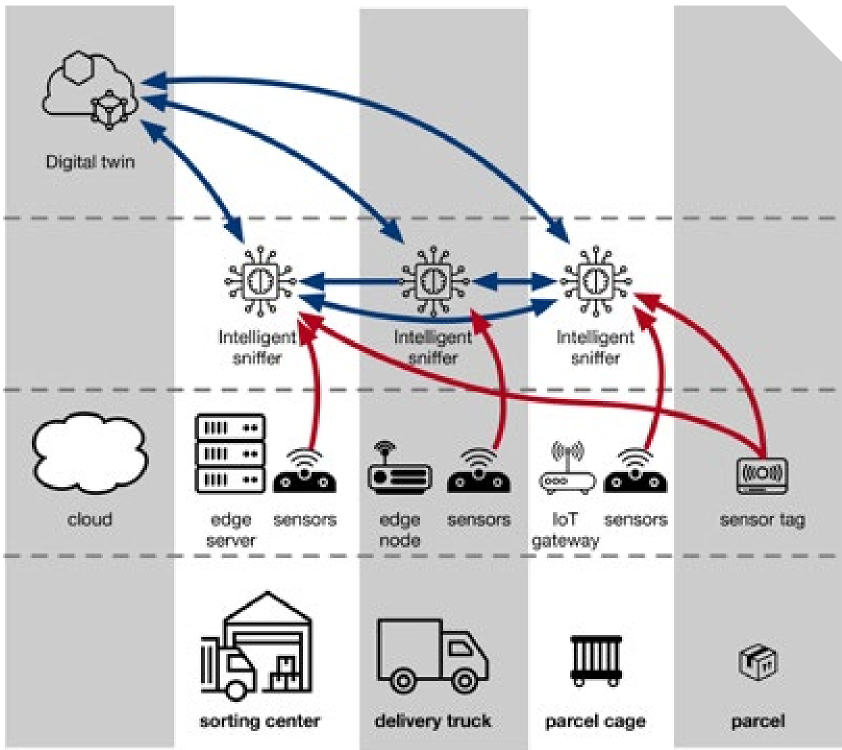


Fig 9. Intelligent routing overview. Intelligent sniffers are deployed on different parts of the compute continuum within the routing infrastructure, receiving data (red) from sensors and exchanging predictions and data (blue) with each other as well as the Digital Twin of intelligent routing.

4.3.1 Digital Twin modeling for pre-emptive error detection

Digital twin technology, where a physical asset or process is mirrored in a virtual model, holds potential in the logistics domain. By leveraging this virtual representation, we can identify and preempt errors that could disrupt the logistics chain.

A digital twin offers a comprehensive, real-time view of object routing, empowering operators to proactively detect potential issues like misrouting, delays due to traffic or weather, and system bottlenecks. Additionally, digital twins enable the simulation of various routing scenarios, allowing logistics companies to stress-test shipment routes. This helps identify weak points in the supply chain and develop contingency plans for potential mis-shipments.

A critical aspect of digital twin modeling is data aggregation, as successful implementation requires real-time data from sources like GPS sensors, RFID tags, and IoT devices. An extensive dataset, compiled from those sources and preprocessed for off-line training, forms the basis for accurate AI model building for anomaly detection in object routing. Predictive analytics powered by machine learning and AI can analyze historical and real-time data to anticipate future disruptions. For instance, deviation from pre-planned route might signal an error in handling – or a rerouting due to external interruptions. Moreover, fluctuations in shipment temperature or sudden stops might signal problems during transit.

The predictive insight gained from such an AI model allows immediate action, as digital twins automatically identify deviations from expected shipment behavior. For example, the unexpected route change could trigger alerts and provide alternative routing solutions. These insights also enable logistics operators to dynamically correct routes or redirect shipments to alternative hubs when a mis-shipment is imminent.

Further, digital twins should integrate with other intelligent routing and warehousing systems to ensure that error detection and correction are not isolated to a single shipment but optimized system-wide. Collaboration among stakeholders—carriers, warehouses, and customers—further enriches digital twin modeling by offering a comprehensive view of the logistics network, fostering proactive and agile decision-making.

In summary, digital twins offer predictive insights, anomaly detection, and dynamic rerouting, which enable more intelligent and resilient logistics networks within the emerging 6G ecosystem.

4.3.2 AI Agent design for Intelligent Sniffer

The Intelligent Sniffer and digital twin approaches are both integral to improving logistics efficiency, though they serve different purposes and complement each other in meaningful ways. The digital twin models the entire shipment route as a virtual representation, providing a macro-level view to anticipate disruptions and mis-shipments. In contrast, the Intelligent Sniffer functions as an AI-driven software agent focused on real-time anomaly detection and immediate error correction at the micro level.

The digital twin leverages comprehensive data aggregation to simulate various routing scenarios, allowing logistics operators to foresee potential issues like system bottlenecks, misrouting, or adverse weather conditions. This proactive identification empowers decision-makers to pre-emptively develop contingency plans or redirect shipments before problems occur. The digital twin integrates seamlessly with management systems, allowing optimization at a systemic level.

On the other hand, the Intelligent Sniffer agent is designed for adaptive monitoring while accompanying shipments or migrating across edge infrastructure. Its microservices-based architecture enables modular handling of tasks such as data aggregation, anomaly detection, predictive analytics, and reporting. The agent collects data from IoT sensors and contextual information from surrounding environments to offer immediate anomaly detection and alerting capabilities. By recognizing patterns through machine learning models, it provides real-time alerts and actionable insights for operators to act upon. The Intelligent Sniffer employs edge computing to minimize latency and make quick, localized decisions.

While the digital twin provides a holistic view of the logistics chain, identifying potential errors across entire networks, the Intelligent Sniffer offers detailed, in-situ monitoring to catch anomalies immediately and provide corrective actions. The Sniffer's localized and automated decision-making is supported by digital twin insights to optimize routing at the macro level.

Together, these two approaches synergistically contribute to the overall improvement of the logistics network: the digital twin ensures proactive planning, and the Intelligent Sniffer guarantees rapid reaction to in-transit disruptions. Both systems support the vision of intelligent routing within 6G wireless networks by offering complementary perspectives for efficient, adaptive logistics management.

4.3.3 Data and knowledge migration

Data and knowledge migration aims to provide actionable information wherever and whenever needed. The process involves transferring relevant data and predictive insights across different entities and environments within the logistics chain.

The first step is edge-to-cloud coordination, where data collected from IoT devices embedded in shipments and surrounding infrastructure is processed at the edge to facilitate immediate, localized decision-making. Data that requires further analysis or contextualization is migrated to cloud platforms, where global predictive models and comprehensive datasets refine insights. In addition, the Intelligent Sniffer must aggregate contextual data from sources like GPS sensors, RFID tags, and environmental monitors, along with conditions like traffic patterns, weather forecasts, and warehouse statuses. This comprehensive data aggregation enables a holistic understanding of the logistics chain.

Predictive models, which are continuously updated with new edge data, may be transferred to the cloud for broader training, enhancing accuracy and relevancy. These refined, cloud-hosted models are then disseminated back to edge nodes to provide optimized local predictive analytics. A microservices architecture supports this data exchange, with each service responsible for a specific function like anomaly detection or routing analysis, and communication happening through lightweight data protocols.

Furthermore, Intelligent Sniffer agents leverage federated learning to share insights among themselves, building a collective knowledge base without exchanging raw data. This collaborative learning approach improves predictive model accuracy and anomaly detection throughout the logistics chain. To ensure the security and trustworthiness of data and knowledge migration, authentication and encryption protocols safeguard sensitive information during transfers.

Through effective data and knowledge migration, the Intelligent Sniffer guarantees that predictive analytics, anomaly detection, and decision-making are consistently optimized, fostering proactive, reliable, and dynamic logistics operations.

4.3.4 On-the-fly re-routing solutions

On-the-fly re-routing solutions minimize disruptions, optimize delivery times, and enhance shipment security. By dynamically adjusting shipment routes in real time, these solutions effectively address unforeseen challenges and evolving conditions. A crucial element is real-time data integration from sources like GPS trackers, traffic management systems, and environmental sensors. This data provides situational awareness, enabling the identification of obstacles such as traffic jams, accidents, adverse weather, or logistical bottlenecks.

Predictive modeling is another key component. By leveraging historical and real-time data, predictive analytics models forecast potential delays or disruptions along planned routes. These models identify patterns or trends that could indicate future problems, allowing alternative routes to be suggested before issues arise, thereby avoiding delays and optimizing delivery times.

Multi-criteria decision-making frameworks ensure that alternative routes are aligned with operational goals. Re-routing algorithms consider multiple factors, including cost, delivery deadlines, shipment security, and regulatory requirements, to identify optimal alternatives. Collaborative planning is also essential, requiring transparent communication among carriers, warehouses, and clients to align new routing decisions with stakeholder priorities.

Edge computing and autonomous decision-making capabilities allow re-routing decisions to be made swiftly without centralized servers, reducing latency. These autonomous systems can automatically adjust routes based on preconfigured rules and predictive insights, minimizing the need for human intervention. For these systems to work efficiently, they must be integrated into resilient logistics networks capable of adapting to changes in shipment volume, route availability, and regulatory constraints. This ensures that re-routed shipments remain within safe and efficient logistical channels.

A feedback loop provides for continuous improvement. Every re-routing action generates valuable data that refines predictive models and improves future decisions. By constantly enhancing their predictive capabilities, these solutions become more accurate, reliable, and intelligent over time. On-the-fly re-routing solutions, supported by real-time data, predictive modeling, and autonomous decision-making, ensure that logistics networks can quickly adapt to changing conditions, optimize delivery times, improve operational resilience, and ultimately enhance customer satisfaction.

4.4 Consolidated sorting

Consolidated sorting in shipment delivery systems often relies on simple, inflexible rules that do not consider real-time data, leading to suboptimal sorting of orders. A main problem that yet needs to be solved is the limited capacity of shipment lockers, which can result in shipments being sent to the wrong location. Consolidating shipments in sorting centers would allow them to be delivered to the same pickup point, but the current sorting process only occurs at the barcode level. By implementing receiver-level sorting, it would be possible to ensure that multi-part shipments arrive together at the same time and place.

To address these challenges, the work in this area could face the challenges and leverage the opportunities of 6G communications and real-time distributed data analysis for the creation of globally optimized consolidated sorting strategies [17]. In this context, the integration of 6G technologies such as edge computing, IoT, and AI into the sorting process is pivotal. These technologies enable real-time data analysis, enhancing decision-making and operational efficiency in consolidated sorting.

The goal is to create flexible solutions that can adapt to changing conditions in real time and improve both palleting and consolidation. The main enablers for this work are the opportunities provided by IoT devices such as smart labels, 6G wireless connections, and distributed computing in local and hyperlocal edge servers, which can integrate real-time heterogeneous data sources and produce actionable information.

To optimize the multiple heterogeneous parameters involved in consolidated sorting, this research area explored the feasibility of iterative and Bayesian optimization algorithms that reduce the search space to reach near-optimal solutions, constructing statistical approximations of the unknown shipment parameters. This involves the use of both model-driven deterministic algorithms and data-driven reinforcement learning agents.

The process starts with the study of the existing situation and the creation of synthetic and simulated datasets. In this context, these data can be incorporated into machine learning and machine vision systems that are in turn used to identify, measure, and classify shipments into suitable categories and locations, improving the sorting process. Edge computing can process data locally at sorting centers, reducing latency and ensuring timely sorting decisions.

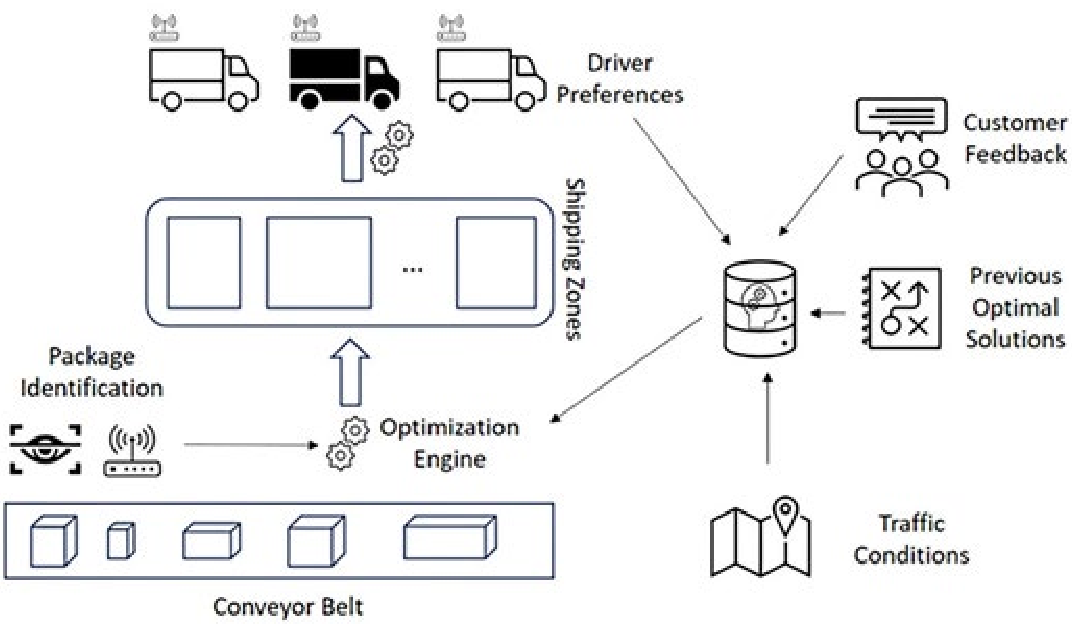


Fig 10. Consolidated sorting using computer vision, ML-augmented optimization, and 6G communication and sensing.

4.4.1 Exploration of Technological Opportunities for Consolidated Sorting

The current consolidated sorting process in logistics relies heavily on predetermined rules and lacks real-time data adaptability, leading to inefficiencies. With the introduction of 6G technology, there's potential to revolutionize this process by integrating real-time data and enhancing communication capabilities. The use of IoT devices, such as smart labels, alongside 6G connectivity, can significantly improve the sorting accuracy and adaptability to changing conditions.

Machine learning and computer vision are set to play crucial roles in identifying and classifying shipments beyond traditional barcode scanning. These technologies offer the potential to automate and refine sorting processes, addressing existing issues like limited shipment locker capacity and improving receiver-level sorting. The focus is on using real-time data, facilitated by 6G's high-speed and low-latency networks, to move towards a more dynamic, responsive sorting system.

This section assesses the technical feasibility, operational impacts, and the economic viability of integrating 6G into consolidated sorting. They will also outline an implementation plan, taking into account the iterative optimization algorithms that 6G enables, and the potential need for new infrastructure and training [18]. The goal is to transition from the current state to a more advanced, efficient, and flexible sorting system that leverages the full capabilities of 6G technology.

The Current State of Consolidated Sorting

Consolidated sorting within logistics centers currently relies on established methods that are largely static, depending on pre-set rules and manual inputs. This system is often constrained by its limited ability to process real-time data, which results in a less than optimal sorting of shipments. Typically, sorting is conducted based on barcode scans that direct shipments through a fixed series of conveyors and chutes. This method, while functional, does not accommodate the complexities of real-time variations in package flow or changes in delivery requirements.

The primary limitations include the inability to dynamically allocate resources based on real-time demand, restricted flexibility in handling varying shipment sizes and types, and the dependency on manual intervention for exceptions. These challenges lead to bottlenecks, especially during peak periods, and can cause delays and increased handling times. In addition, the capacity issues of shipment lockers, often resulting in misplacements and delivery inefficiencies, signify the need for more advanced sorting mechanisms that can adapt to the continuously changing logistics landscape.

The integration of real-time data in the sorting process has the potential to significantly improve these operations, but the current technology infrastructure in many logistics centers is not fully equipped to handle such integration. As a result, there is a pressing need for technological advancements that can bridge this gap and modernize the sorting process to meet the demands of a rapidly evolving market.

Opportunities Afforded by 6G and Real-Time Data

The integration of 6G communications into consolidated sorting processes presents a substantial opportunity to address current limitations by leveraging the high bandwidth and low latency that 6G offers. These advancements are expected to enable the collection and analysis of real-time, heterogeneous data from a variety of sources across the sorting facility. With 6G, data from sensors on shipments, environmental conditions within the sorting center, and even external factors like traffic and weather can be integrated into a centralized system for immediate action.

The ability of 6G to handle massive data streams simultaneously means that sorting systems can become significantly more responsive and adaptive. Real-time data can inform machine-learning algorithms to make predictive adjustments to sorting decisions, leading to a more efficient allocation of shipments to the correct routes and destinations. This not only improves sorting accuracy but also increases throughput and reduces delays caused by manual sorting errors or system inflexibility.

Furthermore, 6G enables a higher degree of automation in shipment sorting by allowing systems to communicate with each other within microseconds. This can lead to a more synchronized operation, where conveyor speeds, sorting arms, and routing decisions are all adjusted in real time based on the current data, optimizing the flow of shipments through the facility. The potential for improved real-time decision-making and automation with 6G technology can transform consolidated sorting into a more flexible, efficient, and reliable process, meeting the increasing demands of modern logistics operations.

The Role of Machine Learning and Computer Vision

The utilization of machine learning and computer vision in the realm of consolidated sorting is set to advance significantly with the implementation of 6G technology [19]. Machine learning algorithms, fed with vast amounts of data that 6G networks are capable of transmitting, will greatly enhance the accuracy and efficiency of sorting operations. These algorithms can predict and adapt to sorting needs in real time, learning from ongoing operations to continuously improve the sorting logic and decision-making processes.

Computer vision, when combined with 6G's capacity for rapid data processing, can extend beyond basic barcode scanning to sophisticated recognition of package contents, conditions, and even subtle labeling details that might be missed by traditional scanners. This level of detail enables more nuanced sorting criteria, which can be particularly crucial for handling special care items or optimizing the packing of mixed-size shipments.

Furthermore, the integration of machine vision with machine learning creates an intelligent system capable of real-time identification and classification of shipments. This system can dynamically adjust to changing shipment characteristics and delivery demands, streamlining the sorting process. By recognizing patterns and anomalies, it can also provide valuable insights for predictive maintenance of sorting machinery, reducing downtime and prolonging equipment life.

The future of consolidated sorting with 6G will likely see these technologies converging to create a seamless, automated flow of shipments through logistics centers. The improved data-driven intelligence will minimize the need for manual intervention, allowing for a faster response to real-time logistics scenarios and ultimately leading to a more resilient supply chain.

Machine learning techniques for algorithm selection and algorithm configuration (e.g., graph neural networks) can learn from previous sorting results to handle novel sorting needs [20]. This model-driven approach can speed up the consolidated sorting process and provides several sorting results to address multiple objectives provided by the decision makers.

The trained model is continuously adapted and enhanced with ongoing data and feedback from workers, drivers and customers. For example, the optimization system can encode workers' know-how in packaging and historical routes implying drivers' preferences. The system can also leverage natural language processing techniques in customer feedback analysis to improve future delivery solutions.

ML-augmented constraint optimization (CO) integrates ML models into effective CO solvers to predict approximate solutions for CO problems such as consolidated sorting and vehicle routing [21]. Some real-world CO problems may contain objectives and constraints which are not explicitly formulated. The data collected by wireless sensors via 6G communication, as well as optimal solutions in the past, offers a valuable source of information to learn these objectives and constraints in an end-to-end optimization process. This approach facilitates Packaging-as-a-Service operations through implementing optimization objectives and constraints defined by the customers or learned from data.

We implement and train a prediction engine to estimate the parameters of the objectives and constraints for each consolidated sorting problem. Then, the optimization engine uses the predicted parameters to compute the optimal solution. The solution is executed and evaluated to augment the dataset for enhancing the prediction and optimization engines in solving future consolidated sorting instances.

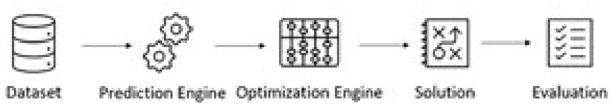


Fig 11. ML-augmented constraint optimization

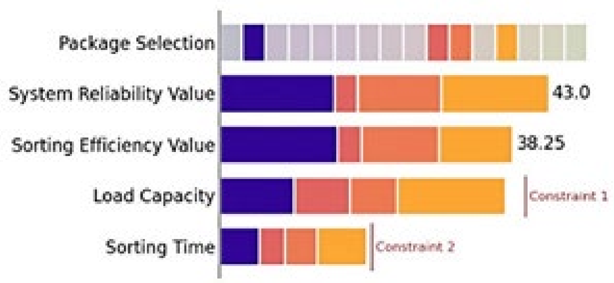


Fig 12. Multi-objective consolidated sorting based on predicted reliability and efficiency values, under the constraints of truck loads and sorting time.

Table 9. KPIs for Consolidated Sorting focusing on the integration of 6G technology and emphasizing multiobjective optimization.

KPI Description	Measurement Method	Relevance of Multiobjective Optimization	ML-related KPIs	Expected Value if Achieved
Increase in Sorting Accuracy	Percentage reduction in sorting errors	Optimized decision-making based on real-time data and enhanced shipment identification	Mean squared error (MSE), root mean squared error (RMSE), mean absolute error (MAE), mean absolute percentage error (MAPE)	Higher accuracy leads to fewer misplacements and increased operational efficiency
Reduction in Sorting Time	Decrease in average time per sorting operation	Faster processing through automated and data-driven systems, utilizing real-time adjustments	MSE, RMSE, MAE, MAPE	Quicker sorting times improve throughput and customer satisfaction
Enhanced Adaptability to Load Variations	Measurement of system's response time to load changes	Dynamic adjustment to varying shipment volumes and types, leveraging iterative and Bayesian optimization algorithms	MSE, RMSE, MAE, MAPE	Increased ability to handle peak loads and unusual sorting scenarios
Improved Utilization of Sorting Capacity	Ratio of utilized sorting capacity to available capacity	Optimal allocation of resources, balancing efficiency with real-time demand	MSE, RMSE, MAE, MAPE	Better utilization of existing infrastructure, reducing the need for additional investment
Reduction in Manual Interventions	Tracking the frequency of manual interventions in the sorting process	Advanced algorithms reducing reliance on manual inputs, adapting to changing logistics variables	Accuracy, F-score	Lower labor costs and reduced error rates due to manual handling
Increase in System Reliability	Uptime percentage and frequency of system failures	Stable sorting operations supported by model-driven deterministic algorithms	MSE, RMSE, MAE, MAPE; Accuracy, F-score	Consistent operational performance, reducing downtime and maintenance costs

4.4.2 Feasibility Analysis of 6G-Enabled Consolidated Sorting

A feasibility analysis of integrating 6G technology into consolidated sorting systems is crucial to understand the practicality of such an undertaking. This analysis must consider the technical requirements, the economic impact, and the operational changes necessary to leverage 6G's capabilities effectively. Technically, the deployment of 6G in logistics centers necessitates a comprehensive evaluation of current infrastructures, the potential need for new hardware, and the compatibility of existing systems with 6G standards. The economic viability hinges on a cost-benefit analysis that weighs the initial investment against the long-term gains in efficiency, accuracy, and potential revenue growth due to improved service levels.

Additionally, operational feasibility must be assessed to determine how 6G will alter current sorting workflows, what training or hiring of specialized personnel might be required, and how to manage the transition to minimize disruption. Risks must also be managed, particularly concerning data security, system reliability, and the potential for technological obsolescence. This section will delve into these aspects, providing a detailed overview of the challenges and opportunities that 6G presents for the future of consolidated sorting in the logistics industry.

Technical and Economic Considerations

The technical feasibility of integrating 6G technology into consolidated sorting revolves around the capacity to handle and process the vast data streams that 6G networks facilitate. Existing logistics systems must be evaluated for their ability to upgrade to 6G compatibility, including the assessment of hardware and software requirements, data handling capacities, and the integration of advanced machine learning and computer vision technologies. The robustness of 6G to support the high-frequency data exchange will also be tested, ensuring that the systems can operate in the ultra-reliable low-latency communication (URLLC) mode that 6G networks promise.

From an economic standpoint, the cost implications of adopting 6G must be carefully analyzed against the backdrop of projected efficiency gains and long-term operational cost savings. The investment in 6G infrastructure, including sensors, edge computing devices, and network upgrades, needs to be justified by a clear return on investment (ROI) model. This model should factor in not just the direct financial benefits, such as reduced labor costs and increased throughput, but also indirect benefits like enhanced customer satisfaction, reduced error rates, and the flexibility to scale operations quickly.

In a sense, the technical assessment must confirm that 6G can be seamlessly integrated into the logistics ecosystem without prohibitive costs, while the economic analysis must validate that the investment is sound and promises a viable financial future for businesses adopting this new technology.

Operational Feasibility and Risk Management

In assessing the operational feasibility of implementing 6G in consolidated sorting, it's essential to consider the implications on existing workflows and processes. This involves understanding the changes that 6G technology will bring to the sorting operations, such as increased automation and the need for real-time data processing. The adaptation of current operational practices to accommodate these changes is crucial, and it may include redefining job roles, updating protocols, and introducing new standard operating procedures.

Training and development are key components in this transition. Staff at all levels will need to be trained not only on how to operate new 6G-enabled systems but also on how to interpret and act upon the real-time data and insights these systems provide. This training should cover technical aspects for IT and engineering staff, as well as operational aspects for floor managers and front-line workers.

Risk management is another critical aspect. The introduction of any new technology brings inherent risks, including technical failures, cybersecurity threats, and potential data breaches. In the case of 6G, there's also the risk of dependency on continuous network availability and the potential impact of network downtimes on sorting operations. Identifying these risks and developing robust mitigation strategies, such as backup systems, fail-safes, and comprehensive cybersecurity measures, is vital for a smooth transition.

Furthermore, the risk of obsolescence should be considered, as technology in the telecommunications field evolves rapidly. Ensuring that the 6G infrastructure and related systems are upgradable and adaptable to future advancements will help safeguard the investment and maintain operational efficiency over time. The following table 10 shows different risks and possible mitigation strategies.

Table 10. Risks and possible mitigation strategies.

Risk Description	Probability	Severity	Mitigation Strategies
Technical Failures: System malfunctions or breakd owns	Medium	High	Regular maintenance and checks. Implementing redundant systems. Continuous staff training on troubleshooting.
Cybersecurity Threats: Unauthorized access or attacks	High	Very High	Robust cybersecurity protocols. Regular software updates and patches. Employee training on cybersecurity best practices.
Data Breaches: Loss or theft of sensitive information	Medium	Very High	Strong encryption methods. Access control and monitoring. Frequent security audits and compliance checks.
Rapid Technological Obsolescence: Technology becoming outdated quickly	High	Medium	Choosing scalable and adaptable technology solutions. Staying updated with industry trends. Planning for regular technology upgrades.
Integration Challenges: Difficulties in integrating new technology with existing systems	Medium	High	Phased implementation approach. Pilot testing before full-scale roll-out. Technical support from vendors.
Operational Disruption: Changes impacting daily operations	Medium	High	Detailed change management planning. Staff training and gradual process integration. Clear communication and feedback channels.
Cost Overruns: Exceeding the budget in the implementation process	Medium	High	Comprehensive budgeting with contingencies. Regular financial reviews.

Optimization Algorithms for Sorting

The implementation of 6G-enabled consolidated sorting introduces the need for sophisticated optimization algorithms capable of handling and interpreting the vast influx of real-time data. The feasibility of these algorithms plays a crucial role in the successful deployment of 6G technology in logistics systems. Various algorithmic approaches are pivotal for maximizing the potential of 6G in sorting operations.

Key to this exploration are iterative and Bayesian optimization algorithms. These algorithms are designed to efficiently navigate through complex data sets, identifying the most effective sorting strategies under varying conditions. Iterative optimization provides a methodical approach to refining sorting processes, gradually improving outcomes through repeated cycles of analysis and adjustment. Bayesian optimization, on the other hand, offers a probabilistic framework that is particularly adept at dealing with uncertainty and incomplete information, making it well-suited for dynamic environments where conditions continuously evolve.

The integration of model-driven deterministic algorithms should also be examined. These algorithms can provide a stable and reliable foundation for sorting decisions, using predefined models based on historical data and established logistics patterns. In contrast, data-driven reinforcement learning agents offer an adaptive approach, continuously learning and evolving based on new data and outcomes. This adaptability is crucial in environments where logistical variables and constraints are constantly changing.

4.4.3 Implementation Plan for 6G-Enabled Consolidated Sorting

Developing an effective implementation plan is crucial for the successful integration of 6G technology into consolidated sorting processes. This plan needs to be comprehensive, addressing the transition from current operations to a future state where 6G-enabled technologies are fully integrated and operational. The plan should be structured in a phased approach, ensuring a smooth transition, minimizing disruptions, and allowing for adjustments based on interim evaluations.

In the development of a phased roll-out strategy for integrating 6G technologies into sorting systems, it is proposed that a structured, step-by-step implementation is crucial for ensuring seamless adaptation and minimizing operational disruptions. Initiating pilot programs allows for the testing and refinement of the technology within controlled environments, gradually expanding its application based on demonstrated success and scalability. This approach is not only pivotal for assessing the technology's integration into existing systems but also for mitigating risks that may arise during its adoption.

The first phase should focus on the groundwork, involving detailed assessments of current logistics infrastructure, necessary upgrades, and the integration points for 6G technology. This includes identifying the hardware and software requirements, planning for the deployment of IoT devices and edge computing solutions, and preparing the existing IT infrastructure for 6G compatibility. Illustrative examples and hypothetical case studies can demonstrate how 6G technologies enable dynamic routing and sorting of packages. For instance, envision a scenario where IoT devices and smart labels on packages provide a continuous stream of data, which is then used to dynamically route and sort packages to optimize logistics operations and cargo space utilization. These applications highlight the practical benefits of 6G technologies and underscore their potential to revolutionize traditional sorting methods.

Additionally, the culmination of this phase should encompass a pilot program, targeting specific areas within the logistics chain to test and refine the integration of 6G technologies in a controlled environment. The integration of IoT devices and edge computing forms the core of this strategy, empowering sorting systems to leverage real-time data for dynamic decision-making. By processing data locally at the edge, systems benefit from reduced latency and enhanced responsiveness, thereby increasing operational efficiency and accuracy. Such integration marks a significant shift in sorting processes, transitioning from static to adaptive systems capable of handling real-time variability in package information and sorting requirements. Pilot programs are essential in evaluating the effectiveness of these technologies in real-world settings, providing crucial insights into efficiency improvements, cost savings, and customer satisfaction. The data derived from these pilots should guide decisions on scaling the technology, ensuring that the transition to full-scale deployment is based on solid empirical evidence and a well-founded expectation of significant operational benefits.

Subsequent phases of the implementation should expand upon the insights gained from the pilot program, gradually scaling up the implementation across different areas of the logistics operations. This includes broader integration of machine learning algorithms for sorting, expanded use of IoT devices throughout the logistics chain, and full utilization of 6G's capabilities for real-time data processing and decision-making. Each phase should be carefully monitored, with key performance indicators (KPIs) established to measure success and guide further implementation steps. Training and change management are integral throughout the implementation process. Staff at all levels will require education and training on the new systems and processes, ensuring they are equipped to handle the technological advancements effectively. Additionally, continual risk assessment and management will be vital to address any challenges or issues that arise during the implementation phases. By the end of the implementation, a plan should detail strategies for long-term sustainability and scalability, ensuring that the 6G-enabled sorting system remains adaptable and effective in the face of future technological advancements and changing market demands.

By the end of the implementation, evaluating the impact of 6G-enabled systems involves using quantitative and qualitative metrics. Key performance indicators such as reduced sorting errors, improved sorting speed, and enhanced system reliability are crucial for measuring the operational improvements brought by these technologies. Anticipated outcomes include heightened efficiency and cost reductions, alongside elevated levels of customer satisfaction, which would showcase the direct benefits to the business and its clientele.

The success of the implementation heavily depends on collaboration and partnerships with technology providers, logistics companies, and research institutions. Such collaborative efforts are vital in driving the development and successful implementation of cutting-edge sorting solutions, leveraging collective expertise and resources to push the boundaries of what 6G technologies can achieve in logistics.

The integration of 6G technologies into consolidated sorting systems suggests a future transition towards more efficient, reliable, and adaptive logistics operations, but their efficient implementation requires careful planning, pilot testing, and strategic implementation, along with robust partnerships and continuous research.

4.5 Real-time ledger management

4.5.1 Motivation of ledger management

This research area is dedicated to the exploration and development of cutting-edge solutions for end-to-end real-time tracking of transport units, signifying a crucial advancement in the domain of logistic management. The core objective encompasses a thorough examination of the methods for identifying objects that require secure logging within a digital ledger. This entails a meticulous definition of both functional and non-functional metadata, delineation of data that warrants inclusion in the ledger versus data that should remain external, and the establishment of guidelines for the retention period of disposable data alongside criteria for data that must be preserved indefinitely.

The impetus for this initiative is rooted in the pressing challenges besieging traditional logistic management practices [14, 16]. Inefficiencies in supply chain coordination, inventory oversight, and transportation route optimization are becoming increasingly pronounced against the backdrop of an intricate global trade network and the surging demand for swift and dependable delivery services. To navigate these challenges, the leveraging of advanced technological frameworks has transitioned from a mere advantage to an absolute necessity.

At the vanguard of this transformative journey are blockchain and the IoT, technologies that promise to redefine the landscape of logistic management. Blockchain technology stands out for its capacity to facilitate secure and transparent tracking of goods from their point of origin to their final destination, thereby ensuring the integrity of the supply chain and significantly mitigating the risk of fraud.

Concurrently, IoT devices offer the unprecedented advantage of real-time monitoring of cargo conditions and precise location tracking, enabling proactive and efficient management and maintenance protocols.

By synergizing blockchain's unparalleled security and transparency with the IoT's dynamic monitoring capabilities, this research area aims to forge a comprehensive toolkit capable of overcoming the multifaceted challenges inherent in traditional logistic operations.

The ultimate vision is to cultivate a logistic management ecosystem that is not only more efficient and resilient but also unequivocally centered on meeting the evolving needs and expectations of customers. Through this endeavor, we are poised to set a new standard for excellence in supply chain management, heralding an era of enhanced reliability and customer satisfaction in the logistics sector.

Thanks to the advent of distributed ledger management, such as blockchain technology, real-time ledger management has become a pivotal force in addressing logistical challenges and fostering innovation. The unique capabilities of blockchain offer several transformative benefits:

Transparency and Traceability:

The append-only database feature of blockchain, accessible across different entities, ensures unparalleled transparency and traceability. This real-time access to data allows for a comprehensive view of transactions and movements across the supply chain, enhancing accountability and visibility.

Security and Fraud Reduction:

The integrity and immutability inherent in blockchain technology safeguard the quality of data. By securing transactions and making data tamper-proof, blockchain significantly reduces the risk of fraud and unauthorized activities, ensuring trust and reliability in logistic operations.

Data Quality and Decision Making:

Enhanced data quality, a direct result of blockchain's secure and immutable record-keeping, provides a solid foundation for accurate and timely decision making. High-quality data is critical for analytics and strategic planning, enabling more informed and effective decisions in logistics management.

Streamlined Processes and Automation:

Blockchain's smart contracts, which execute predefined business rules automatically, streamline logistic processes. This automation reduces paperwork, accelerates transactions, and decreases operational costs, leading to more efficient and cost-effective supply chain operations.

Collaboration and Innovation in Business Models:

By promoting an open logistic system, blockchain technology facilitates unprecedented collaboration opportunities. Businesses can seamlessly work together, sharing data and resources securely, which paves the way for innovative business models and ventures that were previously unattainable.

In essence, this research area leverages blockchain technology to enhance the logistics sector by enhancing transparency, security, and efficiency while opening new avenues for collaboration and innovation. These advancements not only solve longstanding industry challenges but also unlock new potential for growth and efficiency in the global supply chain.

In detail, the usage of blockchain technology expects to gain more efficient and streamlined global trade logistics, enhanced transparency and traceability of the supply chain, and automated commercial processes via smart contracts.

Case:

The current postal world with ledger management

Via the current usage of blockchain technology among Postals, Table 11 shows a set of global projects. In detail, we attempt to scan current blockchain projects from world Postals in the last decade, and most of those projects leverage blockchain technology for crypto stamp systems, voting systems, and track and trace.

Although the most interesting of projects are about the crypto stamp system, especially from the idea of NFT, the key benefits for the crypto stamp system are more regarding financial services which are far from the main demands from e.g., Posti.

Table 11. List of blockchain-based logistic pilots or projects by post from [22].

Country	Year	Project
Australia	2016	Identity storage for verification
	2016	Voting for state elections
Thailand	2017	A blockchain-based data management for tracing and tracking
	2024	A crypto stamp system
Swiss	2018	A private blockchain-based Swiss infrastructure to securely maintain data
	2019	Blockchain-based IoT for pharmaceutical logistic and cold chain via EU guidelines
Egypt	2018	A digital wallet with transaction on Blockchain
	2019	A blockchain-based logistic consolidation center to speed up customs of handling and procedures
Austria	2019	A crypto stamp with NFC-enabled verification and authenticity
Croatia	2019	Cryptocurrency sales and redemption services
	2020	A crypto stamp regarding a physical stamp to pay postage costs
Tunisia	2019	A central bank digital currency regarding to the national currency
	2020	Adoption SWIFT Global Payment Innovation for international transfers
	2021	A central bank digital currency and private wallet
USA	2020	A blockchain mail-in voting system
	2021	A crypto stamp system
	-	A distributed identity for postal logistic use cases
Faroe Islands	2022	A crypto stamp system
France	2023	A crypto stamp system
Italy	2017	A loyal program that rewards to loyal consumers
Liechtenstein	2021	A crypto stamp system
United Arab Emirates	2021	A crypto stamp system
Germany	2023	A crypto stamp system

From Posti's insights and demand, an attention of blockchain-based track and trace system is the main usage from this proposal despite many other novel usages in both postal logistics and financial services. The current track and trace Posti system can be classified in two procedures, international and domestic processes. The international logistic is based on Universal Postal Union (UPU) protocol or point-to-point agreement. Meanwhile, the domestic process is following Posti Event Tracking System (PETS) or SAP. However, this track and trace system does not have an openness feature which means the lack of connection among logistic operators. In other words, the connection among logistic operators or third-Party Logistic (3PL) operators have to be arranged via point-to-point agreements. Consequently, the extension of the current system is slow and not efficient.

From the Posti demand for future track and trace system leveraging blockchain technology, a collaborative postal platform involves diverse logistic operators, for example, DHL, Matkahuolto, Schenger, Posti, PostNord and even 3PL operators (i.e., transportation and warehouse operators) playing a part of the domestic logistics. Moreover, UPU mentions the crucial role of blockchain technology in the growth of track and trace system. Hence, Posti's blockchain-based track and trace system promises a trend to follow and adapt the UPU upgrade as a sub-chain system, as green regions in Figure 13, in a whole hierarchical blockchain-based track and trace system. The figure illustrates a hierarchical track and trace system where each postal country organizes domestic logistics, as the green regions, and UPU blockchain-based track and trace system, as the pink area, manages the connectivity among Postals.

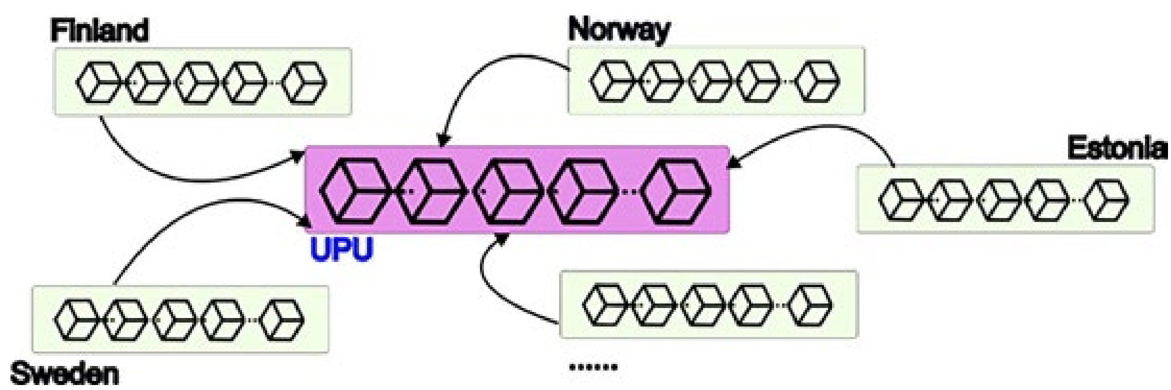


Fig 13. ML-augmented constraint optimization

Leveraging the advantages offered by blockchain technology, it can be applied to a diverse array of postal logistics scenarios as detailed in Table 12. These use cases are designed to showcase the implementation of a system that not only achieves cost efficiencies but also establishes a network characterized by its trustworthiness and reliability.

This dual focus on reducing operational expenses while enhancing the security and transparency of transactions exemplifies the transformative potential of blockchain technology in streamlining postal logistics operations. In addition, leveraging blockchain technology for Posti track and trace system is the first step for further developments regarding Table 11 with voting systems, financial services, and crypto stamp system.

Table 12. Use cases with blockchain technology for Posti.

Use cases	Objectives	Main values	Success metrics	Benefits and impacts
Certificate of origin	A platform for creating and validating certificates	Reduce times for creating and validation	Throughput Latency Experience	Improve the efficiency and human experience Reduce failure or fraud Shorten customs process
Crypto stamps	Automate postal settlements and track history data Potential artistic or cultural value	Decrease costs for postal settlements	Throughput and latency	Enhance the human experience Global accessibility
Custom and handling	Enhance openness with accelerating customs and international flows	Single source for validating documents	Throughput, latency, and complexity cost	Improve the human experience Enables
Digital post office box	Support reliability and convenience in mail delivery and verification	Enable verification document service	Confidentiality and accessibility	Enhance the human experience
Reverse logistics for returns	Reduce time and effort cost on reverse logistic processes	Clear information to reverse or return shipments	Throughput and latency	Enhance human experience
Track and trace	Enhance transparency between stakeholders	All stakeholders trace and track shipments with transparency	Accessibility, availability, and authorization	Enhance the trust and connectivity among stakeholders

4.5.2 Technologies of ledger management

Digital signature in ledger management

Special focus is on the options of digital signature and utilization of real-time ledger technology, which would enable improved inter-operability, automatized operations and increased reliability of transporting units between operators. This would lead to improved efficiency and to minimized errors of end-to-end deliveries. The study includes interfaces and protocols of existing systems. Large-scale scalability of the system will be a key requirement when conducting the system level study.

Potential distributed ledger technologies in logistics

Distributed ledger technology, particularly blockchain, offers significant advantages to the logistics industry by addressing gaps that arise from the underutilization of this technology. [16] highlight how the logistics sector can benefit from the adoption of blockchain technology. [11] further elaborate on the transformative potential of blockchain, emphasizing its ability to enable real-time tracking of control flows, thereby mitigating risk in management processes. Additionally, blockchain serves as a powerful platform for assimilating vast quantities of IoT data and logging events from various activities, enhancing transparency and efficiency across logistics operations [12].

In terms of accessibility, blockchain technology is categorized into three distinct types: permissionless, consortium, and permissioned platforms, each with unique operational capabilities concerning read and write permissions [13]. Permissionless platforms offer unrestricted read and write access, provided users meet certain criteria, particularly for writing data. Conversely, consortium blockchains limit write permissions to specific entities within a collective, while permissioned blockchains impose restrictions on both reading and writing data for all network participants.

Despite the promising applications of distributed ledger technology, the scalability of blockchain remains a significant challenge, potentially hindering its broader adoption. To address this, researchers are exploring various strategies for enhancing blockchain's scalability, including the Directed Acyclic Graph (DAG) technique, sharding, and interoperability solutions [15]. These approaches present promising avenues for overcoming scalability limitations, thereby facilitating more widespread and effective use of blockchain technology in logistics and beyond. Table 13 displays an overview of blockchain scalability's solutions via different levels of safety, scalability, decentralization, and complexity deployment.

Table 13. Comparison between scaling techniques in distributed ledger technology.

Features	Directed Acyclic Graph	Sharding	Interoperability	Blockchain configuration
Safety	Issues with conflicts from concurrency	Issues with 1% attack from limited nodes in a shard	Issues with adaptation	Issues with parameter tunning
Scalability	Highest	Moderate	Moderate	Lowest
Decentralization	Full	Less hierarchy	Hierarchy	Single chain
Deployment	Advanced complexity	Complexity	Less complexity	Simplicity

Further research questions: Which is a suitable distributed ledger technology for logistics? And even that potential solution to scale up the system to be global connectivity regarding the openness and decentralization of blockchain.

Operation with smart contract

In a comprehensive analysis, [14] elucidate a variety of advantages that blockchain technology offers to enhance logistic operations, showcasing its transformative potential in the sector. Those operations are potential smart contracts or predefined rules which in detail as below:

Enhanced shipment tracking and tracing:	Blockchain technology significantly improves access control and data integrity for stakeholders, facilitating authorized read and write operations. The inherent immutability of blockchain instills trust in the veracity of recorded information, thereby streamlining the processes of shipment tracking and tracing with unparalleled transparency.
Streamlined automation of operations:	By employing smart contracts that execute predefined rules upon meeting specific conditions, blockchain technology introduces a high level of automation in logistical operations. This capability is particularly useful in reacting to environmental conditions, such as traffic congestion, enabling more informed decision-making to optimize resource management effectively.
Robust protection of trade documents:	The core principle of immutability in blockchain plays a crucial role in safeguarding trade documents against tampering and fraud, ensuring the authenticity and non-repudiation of transactional records. This security measure is vital in maintaining the integrity of trade documentation throughout the logistic chain.
Reliable asset certification:	Leveraging the secure and transparent nature of blockchain, the technology extends its utility to the certification of assets. By providing a tamper-proof platform for recording asset credentials, blockchain facilitates trust and reliability in asset transactions and ownership.
Efficient operations management:	Given the voluminous data and transactions inherent in logistics, blockchain emerges as a robust solution for aggregating and managing information. Its capacity to handle large volumes of data aids in optimizing various aspects of operations management, such as alleviating congestion, ensuring load balancing, and improving resource allocation, thereby significantly enhancing the overall quality of logistic services.

While [14] outline a series of operations and services tailored for logistics applications, the implementation of blockchain within IoT contexts opens the door to a broader spectrum of use cases. Specifically, it facilitates the creation of a decentralized database, laying a robust foundation for various other applications. This infrastructure is pivotal not just for data retrieval but also plays a crucial role in decision-making processes and generating personalized recommendations, thereby significantly expanding the utility and applicability of blockchain technology in complex systems, for example, smart shipments, and consolidated sorting.

Further research questions: Which is a qualified design for smart contract in real-time ledger management in logistics? Or pre-defined rules in logistic model that enables the collaboration among stakeholders?

4.5.3 Implementation plan for Integrating 6G and distributed ledger technologies to logistics

Exploring the integration of blockchain technology within the logistics management framework, particularly in the context of emerging 6G networks, presents a forward-looking approach to enhancing transactional transparency and efficiency. This endeavor will involve a comprehensive assessment of blockchain's capability to meticulously record and disseminate information pertaining to every transaction, aligning with the objectives set forth. Concurrently, an in-depth exploration of the prerequisites for 6G technology—spanning connectivity, edge computing, and sophisticated data management—will be conducted to ascertain their alignment with blockchain functionalities.

In the realm of practical application and development, for example the smart campus research infrastructure at the University of Oulu, equipped with an advanced 5G/6G Test Network and an integrated blockchain system, can serve as a dynamic co-creation space. This environment facilitates rigorous evaluation of the technical feasibility, operational dynamics, and scalability potential inherent in the fusion of these technologies. Such an ecosystem is pivotal for real-time ledger management, where blockchain's immutable record-keeping converges with 6G's ultra-reliable, low-latency communications.

Delving deeper into the synergy between the IoT and blockchain, the advent of 6G technology emerges as a cornerstone for enhancing communication frameworks. This is especially pertinent in facilitating real-time connectivity that allows for the seamless exchange of sensor data with blockchain networks, thereby enabling more informed management decisions and operational adjustments. For instance, the integration of real-time traffic data within the blockchain could significantly enhance yard management at warehouses or allow for the flexible reallocation of resources in response to situational demands.

This exploration underscores the transformative potential of blockchain and 6G technologies in redefining logistics management. By harnessing these advancements, logistics operations can achieve unprecedented levels of transparency, efficiency, and adaptability, setting a new benchmark for the sector's future.

4.6 On-site robust connectivity

This research area focused on analysing the surfaced challenges and opportunities in Logistics and 6G connectivity.

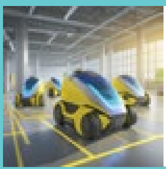
The approach includes integration of the 6G technical enablers and systemic opportunities to the automation needed in shipment IDs, tracking, routing, process, optimization and robotization. Starting point was a study of existing situation utilizing e.g., on-site logistics center visits, research visits from our partners and counter visits to our partners.

Close collaboration with other research areas is required e.g., reflecting the 6G enablers to solutions needed in logistics.

This approach enables to form precise views of current logistics issues and match these views to potential of 6G technologies, leading to planning of the concrete next steps.

4.6.1 On-site activities

On-site logistics can be divided into multiple discrete, but parallel activities jointly contributing to the whole. Each of these parallel activities require specific connectivity solutions to fulfill their requirements. The specific activities include operations including:



Automated guided vehicles (AGVs)/autonomous mobile robots (AMRs) indoors

Sorting, bin picking and packaging

Shipment feeding to sorting machine

Situational surveillance

Work safety

Automated guided vehicles/autonomous mobile robots indoors

AGVs and AMRs can play a significant role in automatisation of otherwise menial work of transporting shipments and goods from one location to another. However, the environment they are operating in is far from trivial; they need to operate in a shared environment with people, conventional forklifts, and continuously altering geography due to loading and unloading. The robust connectivity requirements for AGVs/AMRs mainly relate to indoor location and tracking, as well as collision avoidance.

Indoor location and tracking

In indoor condition global positioning systems do not provide the precision required for automated operations. Indoor location can be obtained by multiple communications technologies including Bluetooth, ultra wideband (UWB), millimetre wave (mmW), WiFi, and cellular but it can also utilise non-signalling based solutions like, machine vision aided with computational tools. However, utilization of non-signalling based solutions require quite significant data communications bandwidth due to the requirement of matching the constantly changing indoor logistics environment with the observed surroundings. A lot of effort and interest is being invested in integrated sensing and communications technologies of 6G (c.f. [10]). Each of the solutions have their pros and cons, and for the on site robust connectivity of logistics they mainly revolve around location accuracy, longevity of the technology, and cost. For AGVs and AMRs equipped with collision avoidance sensors, even the accuracy of Bluetooth (meter range) may be sufficient. Tracking of AMRs and AGVs can be done also using multiple techniques, including constant position update, trajectory calculation and estimation algorithms, or exploiting already well-established technologies in vehicle to everything communications (V2X): cellular, 5G new radio, G5 (dedicated short range communications), or the recent IEEE 802.11bd amendment applying the intelligent transportation systems (ITS) specifications on collaborative awareness messaging and decentralised environmental monitoring messaging. On one hand, if a bundled system for addressing the challenges above is required, a private 5G advanced network may be only option. On the other hand most of the above technologies can be combined produce a similarly functional system.

Collision avoidance

Proximity sensors are required for all automated/autonomous systems to be able to react to sudden changes in the environment or prevent collisions on objects/personnel not participating in the joint digital group environment. The use of ITS-like communications enables automatic notification of unexpected objects/events in the near vicinity to other users of the system. This provides a safer operations environment and it also enables a “see the invisible” automated traffic management system for vehicles and robots traversing the in the highly corridorised environment of a logistics centre.

Sorting, bin picking and packaging

Taking the consolidated sorting to an advanced era requires the extensive use of machine vision enhanced with machine learning and artificial intelligence algorithms. Here the on-site robust connectivity is required to offer several concurrent high-bandwidth data streams to able the transfer of real-time images from the machine vision components. Where the machine vision components cannot be connected to a fiber optic local area network, a sliced cellular environment is a good means for isolating the high priority sorting actions from the other users of the network and also guaranteeing sufficient capacity for the sorting operations.

Automated bin picking requires the AGVs and AMRs above. Hence, bin picking operations require very much the same communications technology solutions as above. In addition, technology similar in sorting is required to traverse in the rows of shelves, identification of the bin items and retrieval of them. The management of bin items on-line is only a marginal addition to the data transfers capacity requirements of the real-time machine vision data. Also bin picking route plan optimisation can be done by the bin picking commissioning entity and any update of the route is only a small data capcity requirement. Automated packaging is from the communications perspective very similar to sorting activity and typically carried out by static machinery that can use fiber optic local are connectivity.

Shipment feeding to sorting machine

The task of smart shipments outlined the technologies that could be used with shipments. There are some challenges in adoption of low-cost RFID tags when feeding the shipments to sorting. Low-cost tags are typically passive and reading them when they are tightly packed together, coming out of a pallet is challenging.

Any probing attempt will reflect multiple tags simultaneously causing reading and cataloguing errors as well as missing shipments. Having multiple tag categories for the various priorities of shipments alleviates the challenge to some extent but increases the complexity of sorting machine communications equipment. In addition, the majority of shipments will have a relatively low priority resulting in the low-cost RFID tag challenge. Furthermore, the challenge of global shipment tag addressing increases the scope of the sorting problem.

The base challenge here is the need to receive temporally disjoint responses from shipments whenever polling them. In case of RFID this would require the tags either to be active or be able to store energy for a brief amount of time from an RFID poll and respond to the polls with a random delay after polling. Another avenue would be to use integrated sensing and communications, narrow antenna beam widths, and analysing the polling responses' signals' characteristics offered by 6G technologies.

Situational surveillance

Another aspect of on-site robust connectivity relates to situational awareness, focusing on the topics of:

- **Loading/unloading surveillance**
- **Shipment indoor location**
- **Personnel location/ worker logistics**
- **Anomalous objects/ people**

Loading and unloading automatic surveillance provides the ability to optimise the handling of input and output flows of shipments. Here machine vision plays a significant role, and the communications system's main requirement is to provide pseudo real-time updates of the observed areas.

Shipments typically have a hierarchic structure in terms of location. Shipments, not in active sorting are placed in pallets, pallets in containers or trucks, and containers in trains, docks, or ships. Therefore, the logical location structure goes with increased capability for location. Shipments do not individually require location capability. Pallets can utilise the same indoor location systems as AGVs and AMRs. Containers and truck should be equipped with technology able to receive the pallets' location signal.

Work safety

Due to the growing automation of logistics centres' operations people need to also become connected in the traffic management system of a centre. In addition to be able to be detected by the automated/autonomous vehicles and robots by having location trackers in their safety gear, people also need to be able to perceive the vehicles and robots in their vicinity and be alerted of a collision trajectory. The byproduct of being connected to the traffic management the centre management have the ability to perceive personnel real-time location for efficient employee placement.

5 Summary and conclusion

6G technology revolutionizes logistics by providing enhanced connectivity, real-time data processing, and robust integration of advanced technologies. This results in improved routing, tracking, sorting, ledger management, and on-site operations, leading to greater efficiency, transparency, and safety in logistics management.

System level

At the system level, the integration of 6G technology in logistics can transform the industry by enhancing the modeling, analysis, and management of complex logistics chains.

Here's a detailed look based on the specified areas:

Effective Modeling Approaches for Complex Systems

- High-Fidelity Simulations: 6G's high-speed data transfer and low latency enable more detailed and accurate simulations of logistics operations. This includes simulating entire supply chains with real-time data integration, which can enhance the understanding of system behavior and interdependencies.
- Scalability: The increased capacity of 6G networks allows for the modeling of larger and more complex systems, integrating numerous variables and data points from various sources across the logistics chain.

Application of Digital Twins in Logistics

- Real-Time Monitoring and Management: Digital twins, virtual replicas of physical assets or processes, can leverage 6G to receive real-time data updates from IoT sensors. This ensures up-to-date monitoring of logistics assets like trucks, containers, and warehouses.
- Predictive Maintenance and Optimization: AI-driven predictive analytics, supported by the data-rich environment of 6G, can analyze the digital twins to forecast potential issues and optimize maintenance schedules, thereby reducing downtime and increasing efficiency.
- Scenario Planning and Optimization: Digital twins can be used to test various logistics scenarios and strategies in a virtual environment before implementation, allowing for optimized decision-making and risk management.

AI-Driven Predictive Solutions

- Predictive Analytics: With the vast amounts of data processed through 6G, AI can predict demand fluctuations, identify potential supply chain disruptions, and recommend proactive measures.
- Automation and Robotics: AI-driven robots and autonomous vehicles can be deployed for tasks like sorting, packing, and last-mile delivery, all coordinated through a 6G network to ensure real-time adjustments and efficient operations.

Seamless Integration Across the Supply Chain

- Interoperability: 6G's ability to connect diverse systems and devices ensures seamless data exchange across the entire logistics network, from suppliers to end customers.
- Real-Time Decision Making: The low latency and high-speed capabilities of 6G enable instant data-driven decisions, which is crucial for dynamic and time-sensitive logistics operations.
- End-to-End Visibility: Enhanced connectivity and data sharing provide complete visibility over the logistics chain, facilitating better coordination and collaboration among stakeholders.

In summary, the deployment of 6G in logistics at the system level offers a transformative potential by enabling advanced modeling, integrating digital twins with AI-driven predictive solutions, and refining key performance indicators. This leads to more efficient, responsive, and sustainable logistics operations.

Smart Objects

6G technology can significantly enhance the capabilities and functionalities of smart objects in logistics by addressing current obstacles and introducing innovative solutions.

Here's an elaboration based on the specified areas:

Improved Transactional Data Transfer

- Seamless Data Exchange: 6G networks can facilitate smooth and instantaneous data transfer between senders and recipients. This enables real-time sharing of shipment information, enhancing transparency and collaboration across the logistics chain.
- Enhanced Data Accuracy: The high-speed and low-latency capabilities of 6G ensure that data is transferred without delays or errors, reducing discrepancies and improving trust between stakeholders.

Concept of Smart Packages

- Embedded ICT Modules and Tags: Smart objects can be equipped with economical ICT modules and tags that leverage 6G connectivity. These modules can include sensors for monitoring various parameters such as temperature, humidity, shock, and location.
- Streamlined Applications: The applications designed for these smart objects can be streamlined to ensure efficient data retrieval and storage. This can include user-friendly interfaces for both senders and recipients to access real-time data about their packages.

Compliance with Regulatory Directives

- Compliance with EU Package Directive: Smart objects can be designed to meet the EU's upcoming package directives by incorporating features such as traceability, accountability, and sustainability metrics. 6G connectivity ensures that all required data can be collected and reported accurately and in real-time.

Enhancing Tracking Functionalities

- Real-Time Location Tracking: With 6G, smart objects can provide precise and continuous updates on their location, allowing for better route optimization and delivery scheduling.
- Condition Monitoring: Sensors embedded in smart objects can monitor the condition of the contents during transit. For example, temperature-sensitive goods can be tracked to ensure they remain within the required temperature range, reducing spoilage and loss.
- Predictive Analytics: The data collected from smart objects can be analyzed using AI and machine learning to predict potential issues and delays, allowing for proactive measures to be taken.

Enhancing Data Retrieval and Storage

- Cloud Integration: 6G enables efficient integration with cloud platforms, where data from smart objects can be stored, analyzed, and accessed globally. This ensures that all stakeholders have access to up-to-date information.
- Data Security and Privacy: Advanced encryption and security protocols facilitated by 6G ensure that the data stored and transferred is secure, protecting against unauthorized access and breaches.

Benefits of Smart Packages with 6G

- Automation: The data from smart objects can automate various processes such as sorting, handling, and delivery, reducing manual intervention and errors.
- Inventory Management: Enhanced tracking capabilities help in maintaining accurate inventory records, improving stock management, and reducing out-of-stock situations.
- Customer Experience: Providing customers with real-time updates and detailed information about their objects enhances their overall experience and satisfaction.

Sustainability and Cost Reduction

- Reduced Waste: Real-time monitoring helps in reducing waste by ensuring that goods are stored and transported under optimal conditions.
- Cost Efficiency: Economical ICT modules and streamlined applications reduce the cost of implementing smart object technologies, making them accessible for wider adoption in the logistics industry.

In conclusion, 6G technology can revolutionize the concept of smart objects in logistics by enabling real-time, accurate data transfer, enhancing tracking functionalities, ensuring regulatory compliance, and improving overall operational efficiency and customer satisfaction.

Intelligent routing

The integration of 6G technology in logistics can significantly enhance intelligent routing by leveraging advanced sensor tags, intelligent sniffers, and digital twins.

Here's an elaboration on how this proposed solution can transform logistics operations:

Utilization of Sensor Tags

- RFID and Sensor Tags: 6G can support the widespread deployment of RFID and other sensor tags on objects. These tags can continuously collect and transmit data about the condition of shipments, such as temperature, humidity, vibration, and location.

- Environmental Monitoring: Sensor tags throughout the sorting and routing infrastructure can monitor environmental factors that affect logistics operations, ensuring that sensitive goods are handled properly.

Real-Time Data from Intelligent Sniffers

- Deployment on Infrastructure: Intelligent sniffers deployed on object containers, delivery vehicles, and sorting infrastructure can gather real-time data on the location and status of shipments. These sniffers enhance the data collected by sensor tags by providing additional context, such as vehicle speed, route conditions, and traffic.

- Predictive Analytics: By combining current and projected location details with environmental data, intelligent sniffers can predict future statuses of shipments, enabling proactive adjustments to routes and handling procedures.

Real-Time Predictive Overview

- Digital Twin Creation: The data from sensor tags and intelligent sniffers is fed into a digital twin of the intelligent routing system. This digital twin acts as a virtual replica of the entire logistics network, simulating the real-world conditions and behaviors of shipments and routes.

- Predictive Modeling: With 6G's high-speed data processing capabilities, the digital twin can continuously update and analyze real-time data, offering predictive insights. It can simulate different scenarios, assess potential disruptions, and recommend optimal routing decisions to avoid delays and minimize risks.

Optimized Route Planning

- Dynamic Route Adjustments: Based on the real-time and predictive data, the intelligent routing system can dynamically adjust routes to optimize delivery times and reduce fuel consumption. This includes rerouting vehicles in response to traffic conditions, weather changes, and other unforeseen events.

- Resource Allocation: The system can efficiently allocate resources such as vehicles and personnel based on current demands and predictive insights, ensuring that logistics operations are always running at optimal capacity.

Enhanced Efficiency and Reliability

- Reduced Delays: By predicting and mitigating potential delays, the intelligent routing system can ensure more reliable delivery schedules, enhancing customer satisfaction.

- Improved Asset Utilization: The system can optimize the use of logistics assets, such as vehicles and storage facilities, by ensuring they are used efficiently and effectively.

Comprehensive Monitoring and Reporting

- End-to-End Visibility: 6G enables comprehensive monitoring of the entire logistics network. Stakeholders can access real-time data and predictive reports on the status of shipments, vehicle locations, and route conditions.

- Regulatory Compliance: The detailed monitoring and reporting capabilities help ensure compliance with various regulatory requirements, such as tracking and reporting conditions for sensitive shipments.

Cost Savings

- Operational Efficiency: The enhanced data collection and predictive capabilities reduce operational inefficiencies, leading to cost savings in fuel, labor, and asset maintenance.

- Reduced Waste: Optimized routing and handling minimize the risk of damage to goods, reducing waste and associated costs.

Sustainability

- Lower Carbon Footprint: Efficient routing reduces fuel consumption and emissions, supporting sustainability initiatives and reducing the logistics industry's environmental impact.

In conclusion, the integration of 6G technology with sensor tags, intelligent sniffers, and digital twins in logistics can revolutionize intelligent routing. It provides real-time and predictive data, optimizes route planning, enhances operational efficiency, and supports sustainability goals, ultimately transforming the logistics landscape.

Consolidated sorting

Incorporating 6G technologies like edge computing, IoT, and AI into the sorting process can revolutionize consolidated sorting in logistics, leading to significant improvements in real-time data analysis, decision-making, and operational efficiency. Here's a detailed exploration of what 6G can do in this context:

Real-Time Data Analysis with Edge Computing

- Local Processing: Edge computing enables data processing at or near the source of data collection (e.g., sorting facilities), reducing latency and bandwidth usage. This allows for instantaneous analysis and action.
- Reduced Latency: With 6G's ultra-low latency, edge devices can quickly process data from sensors and IoT devices, providing real-time insights and enabling immediate responses to operational needs.
- Scalability: Edge computing supports the scalability of sorting operations by distributing computing power across numerous edge devices, ensuring efficient processing even during peak times.

Internet of Things (IoT) Integration

- Comprehensive Monitoring: IoT sensors can be deployed throughout the sorting facility to monitor various parameters such as object weight, dimensions, condition, and environmental factors.
- Automated Sorting: IoT-enabled sorting machines can automatically categorize and route objects based on real-time data, improving accuracy and speed.
- Predictive Maintenance: IoT sensors on sorting equipment can predict maintenance needs by monitoring performance and detecting anomalies, thereby reducing downtime and extending the lifespan of machinery.

Artificial Intelligence (AI) Applications

- Machine Learning Algorithms: AI algorithms can analyze data from IoT sensors and edge devices to optimize sorting processes. For example, machine learning can identify patterns and predict the best sorting routes for different types of objects.
- Adaptive Systems: AI can enable adaptive sorting systems that learn and improve over time, adjusting to changing volumes, object types, and operational conditions without manual intervention.
- Dynamic Resource Allocation: AI can allocate resources such as sorting lanes, labor, and equipment dynamically based on real-time demand and predictive analytics, ensuring optimal utilization.

Enhanced Operational Efficiency

- Streamlined Processes: Real-time data and AI-driven insights streamline sorting processes, reducing manual handling and errors, and increasing throughput.
- Improved Accuracy: Advanced sorting algorithms and IoT data ensure objects are accurately sorted and routed, minimizing misdeliveries and returns.
- Faster Turnaround: The integration of 6G technologies accelerates the sorting process, leading to faster turnaround times for objects and improved customer satisfaction.

Consolidated Sorting Operations

- Unified Platform: A centralized control system powered by 6G technologies can oversee all sorting operations, ensuring consistent performance and facilitating coordination across multiple sorting centers.
- Real-Time Monitoring and Alerts: The system can provide real-time monitoring of sorting operations and generate alerts for any issues, allowing for quick resolution and minimizing disruptions.

Enhanced Data Utilization

- Big Data Analytics: The vast amount of data collected through IoT sensors and edge devices can be analyzed using AI to gain insights into operational trends, inefficiencies, and opportunities for improvement.
- Performance Metrics: Detailed analytics and reporting tools can track key performance indicators (KPIs) such as sorting accuracy, speed, equipment uptime, and labor productivity, helping to continuously refine operations.

Sustainable Practices

- Energy Efficiency: IoT sensors can monitor energy usage and optimize equipment operation to reduce power consumption, contributing to sustainability goals.
- Waste Reduction: Improved sorting accuracy and predictive maintenance reduce waste from damaged objects and equipment failures.

Cost Savings

- Reduced Operational Costs: Automation and real-time decision-making reduce labor costs and operational inefficiencies.
- Maintenance Savings: Predictive maintenance decreases unexpected breakdowns and extends equipment lifespan, lowering maintenance expenses.

In summary, incorporating 6G technologies such as edge computing, IoT, and AI into consolidated sorting operations in logistics offers transformative potential. It enables real-time data analysis, enhances decision-making, and improves operational efficiency, leading to faster, more accurate, and cost-effective sorting processes while supporting sustainability efforts.

Real-time ledger management

Incorporating blockchain technology into logistics management within the 6G network framework can revolutionize real-time ledger management by enhancing transparency, security, and efficiency. The convergence of these technologies in environments like the Smart Campus research infrastructure at the University of Oulu offers a dynamic space to explore their potential. Here's an elaboration on what 6G can do with real-time ledger management in logistics:

Transactional Transparency

- Immutable Records: Blockchain technology ensures that all transactions within the logistics network are permanently recorded in an immutable ledger, enhancing transparency and trust among stakeholders.
- Real-Time Verification: With 6G's ultra-low latency, transactions can be verified in real-time, allowing for immediate updates to the blockchain ledger. This reduces the time lag in recording and verifying transactions, which is crucial for maintaining an up-to-date and accurate ledger.

Enhanced Security

- Secure Data Transmission: 6G provides highly secure communication channels, reducing the risk of data breaches during transaction transmission. This is vital for protecting sensitive logistical data.
- Decentralized Storage: Blockchain's decentralized nature, combined with 6G's robust connectivity, ensures that data is not stored in a single vulnerable location but distributed across a network of nodes, enhancing security against cyberattacks.

Operational Dynamics

- Smart Contracts: Automated smart contracts on the blockchain can execute predefined logistics actions (e.g., payment release upon delivery confirmation) without the need for manual intervention, streamlining operations.
- Reduced Administrative Overhead: By automating transaction recording and verification processes, blockchain can significantly reduce the administrative burden associated with maintaining and auditing logistics records.

Real-Time Data Synchronization

- Instant Updates: 6G's high-speed connectivity ensures that data from various sources (e.g., IoT sensors, RFID tags) is synchronized in real-time across the blockchain ledger. This provides all stakeholders with immediate access to the latest information.
- Global Visibility: The real-time synchronization capability allows for global visibility into the logistics network, enabling better coordination and decision-making across different regions and time zones.

Scalability Potential

- Handling High Transaction Volumes: The combination of 6G's bandwidth and blockchain's distributed ledger technology can handle the high volume of transactions typical in large-scale logistics operations, ensuring scalability as the network grows.
- Adaptive Network Management: 6G's advanced network management features can dynamically allocate resources to support the blockchain infrastructure, ensuring consistent performance even during peak times.

Technical Feasibility

- Co-Creation and Testing: Environments like the University of Oulu's Smart Campus, with its advanced 5G/6G Test Network and integrated blockchain system, provide a platform to test and refine the technical aspects of integrating these technologies. This includes exploring the optimal configurations for latency, throughput, and security.
- Prototyping and Feedback: Such research infrastructures enable rapid prototyping and iterative testing, allowing researchers and industry partners to gather feedback and make necessary adjustments to improve system performance and reliability.

Practical Applications in Logistics

- End-to-End Tracking: Blockchain combined with 6G allows for real-time tracking of goods throughout the supply chain. Each transaction, from production to delivery, is recorded on the blockchain, providing an unbroken chain of custody.
- Regulatory Compliance: Detailed and immutable records help in complying with regulatory requirements by providing transparent and verifiable documentation of the entire logistics process.

Dispute Resolution and Accountability

- Transparent Audit Trails: The detailed records maintained on the blockchain provide a clear audit trail that can be used to resolve disputes quickly and fairly. This enhances accountability by clearly showing who was responsible for each step in the logistics process.
- Proof of Delivery: Blockchain can provide irrefutable proof of delivery, reducing the risk of fraud and disputes over whether goods were delivered as agreed.

In summary, the integration of blockchain technology with 6G networks can greatly enhance real-time ledger management in logistics. This combination offers transactional transparency, enhanced security, operational efficiency, scalability, and practical applications that improve traceability, compliance, and accountability in logistics operations. *The Smart Campus* at the University of Oulu exemplifies an ideal environment for exploring and refining these innovations, paving the way for more robust and efficient logistics management systems.

On-site robust connectivity

6G technology can significantly enhance on-site logistics by providing robust connectivity tailored to the distinct yet concurrent activities that collectively contribute to overall operations.

Here's an elaboration on how 6G can impact each of these specific activities:

Enhanced Navigation and Coordination

- Low-Latency Communication: 6G's ultra-low latency enables real-time communication between AGVs/AMRs and the central control system, facilitating precise navigation and coordination.
- High Bandwidth: The increased bandwidth allows for the seamless transmission of high-definition sensor data and video feeds, improving the robots' ability to detect and respond to their environment.
- Edge Computing: By integrating edge computing, data can be processed locally on the robots or nearby devices, reducing response times and enhancing operational efficiency.

Sorting, Bin Picking, and Packaging

- Edge AI: 6G supports the deployment of AI at the edge, enabling real-time image recognition and sorting algorithms to enhance the accuracy and speed of bin picking and packaging tasks.
- IoT Connectivity: IoT devices and sensors connected via 6G can monitor the status of sorting and packaging equipment, ensuring optimal performance and minimizing downtime through predictive maintenance.
- Automation Integration: Seamless connectivity allows for the integration of various automated systems, ensuring smooth transitions between sorting, picking, and packaging processes.

Shipment Feeding to Sorting Machine

- High Reliability: 6G provides highly reliable connectivity, ensuring that the data and control signals required for the feeding process are transmitted without interruption, crucial for maintaining synchronized operations.
- Robust Network Coverage: Enhanced network coverage ensures consistent connectivity across the entire facility, enabling efficient and uninterrupted shipment feeding processes.

Situational Surveillance

- High-Definition Video Streaming: 6G supports the transmission of high-definition video feeds with minimal latency, allowing for real-time surveillance and monitoring of the logistics site.
- AI-Driven Analytics: AI can analyze surveillance data in real-time, detecting anomalies, potential security threats, and operational inefficiencies.
- Comprehensive Coverage: 6G's robust network ensures that surveillance cameras and sensors can be deployed throughout the facility, providing comprehensive coverage and situational awareness.

Real-Time Safety Monitoring

- Wearable Devices: Employees can use wearable devices connected via 6G to monitor vital signs and environmental conditions, ensuring immediate response to health and safety incidents.
- Proximity Alerts: 6G-enabled sensors can detect the proximity of workers to hazardous areas or equipment, triggering alerts to prevent accidents.
- Emergency Response Coordination: In case of emergencies, 6G's reliable connectivity ensures rapid communication and coordination among response teams, improving the effectiveness of emergency interventions.

Integrated System Management

- Unified Platform: 6G allows for the integration of all on-site activities into a unified management platform, providing real-time visibility and control over the entire logistics operation.
- Data-Driven Decision Making: The high-speed connectivity and real-time data processing capabilities enable data-driven decision-making, improving operational efficiency and productivity.

Enhanced Flexibility and Scalability

- Scalable Network Solutions: 6G networks can easily scale to accommodate the growing number of connected devices and increasing data volumes, ensuring that the logistics operation can expand without connectivity issues.
- Flexible Deployment: 6G's flexible deployment options, including private networks, ensure that connectivity solutions can be tailored to the specific needs of each on-site activity.

In conclusion, 6G technology can revolutionize on-site logistics by providing robust and tailored connectivity solutions for various concurrent activities. From enhancing the coordination of autonomous robots to ensuring real-time surveillance and improving work safety, 6G's capabilities in low-latency communication, high bandwidth, and reliable connectivity enable significant advancements in operational efficiency, safety, and overall performance in logistics operations.

The business potential of 6G in logistics is substantial, offering advancements in speed, connectivity, and data management that can revolutionize the industry. Key potential impacts include:

1 **Enhanced Connectivity and Speed:**

6G is expected to provide ultra-fast data transfer rates and low latency, enabling real-time tracking and monitoring of shipments and assets. This can improve supply chain visibility and responsiveness.

2 **IoT Integration:**

With 6G, the Internet of Things (IoT) can be more seamlessly integrated, allowing for more sophisticated sensor networks and automated systems. This can lead to more efficient warehouse management, predictive maintenance, and inventory control.

3 **AI and Automation:**

6G will support advanced AI applications and automation technologies, facilitating the development of autonomous vehicles and drones for last-mile delivery, as well as robotic systems for warehouse operations, reducing labor costs and increasing efficiency.

4 **Data Management and Analytics:**

The increased bandwidth and processing capabilities of 6G will enable more comprehensive data collection and real-time analytics. This can enhance decision-making processes, optimize routes, reduce fuel consumption, and improve overall operational efficiency.

5 **Enhanced Security:**

6G networks are expected to offer improved security features, crucial for protecting sensitive logistical data and ensuring the integrity of supply chains.

6 **Sustainability:**

By optimizing operations and improving efficiency, 6G can contribute to more sustainable logistics practices, reducing carbon footprints and supporting environmental goals.

Overall, the adoption of 6G in logistics promises to streamline operations, cut costs, and open up new opportunities for innovation and growth.

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