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МАПУВАННЯ ЛАНЦЮГА ПОСТАВОК ТА ІДЕНТИФІКАЦІЯ КРИТИЧНИХ ЛАНОК У СЕКТОРІ ОХОРОНИ ЗДОРОВ'Я

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SUPPLY CHAIN MAPPING AND CRITICAL NODE IDENTIFICATION IN THE HEALTHCARE SECTOR

Анотація. У статті досліджується концепція стратегічного мапування ланцюгів постачання у сфері охорони здоров’я як інструменту підвищення стійкості медичних систем до зовнішніх шоків, криз і надзвичайних ситуацій. Основна увага приділяється методиці ідентифікації критичних вузлів — елементів або точок у ланцюгу, порушення функціонування яких може спричинити масштабні перебої в системі медичного забезпечення. Автор аналізує структуру та взаємодію чотирьох ключових підланцюгів: фармацевтичного (виробництво, імпорт і дистрибуція лікарських засобів), постачання медичних виробів і обладнання, медичних витратних матеріалів (зокрема засобів індивідуального захисту), а також ланцюга постачання крові та кровозамінників. На прикладі України — особливо в умовах пандемії COVID-19 і повномасштабної війни — розкривається, як збої у виробництві, імпорті, логістиці, централізованих закупівлях чи цифровій координації можуть мати каскадний ефект, що призводить до системних збоїв у наданні медичних послуг. Розглядаються як вертикальні критичні вузли (наприклад, єдині постачальники діючих речовин або ключові логістичні склади), так і горизонтальні точки перетину (лікарні, платформи закупівель, цифрові системи обліку). Підкреслюється важливість досягнення глибокої (Tier N) прозорості ланцюгів постачання, інтеграції цифрових платформ, диверсифікації джерел постачання, розвитку партнерств між державним і приватним секторами, а також створення адаптивних стратегічних запасів і підвищення рівня міжгалузевої координації. Стаття поєднує прикладний аналіз, аналітичне моделювання та системні підходи до управління ризиками у сфері охорони здоров’я, пропонуючи універсальну міждисциплінарну методику. Такий підхід дозволяє не лише виявити вразливі точки, а й сформувати практичну основу для модернізації медичних систем, планування безперервності обслуговування, оцінки ризиків і оперативного реагування на нові виклики в умовах високої невизначеності, геополітичної напруги, глобальних потрясінь і трансформацій постачання в умовах обмежених ресурсів і нестабільного середовища.

Ключові слова: мапування ланцюгів постачання, стійкість ланцюгів постачання, охорона здоров’я, Україна

Annotation. This article explores the concept of strategic supply chain mapping in the healthcare sector as a practical and evidence-based approach to enhancing the resilience of health systems in the face of external shocks, systemic crises, and emergency disruptions. It presents a comprehensive methodology for identifying critical nodes—

specific elements or intersection points within the healthcare supply chain whose failure could lead to cascading breakdowns in healthcare delivery. The analysis focuses on four major sub-chains: pharmaceuticals (including the production, importation, and distribution of medicines), medical devices and equipment, medical consumables (notably personal protective equipment), and blood and blood substitute logistics. Using Ukraine as a case study—particularly under the acute pressure of the COVID-19 pandemic and the ongoing full-scale war—the article illustrates how interruptions in logistics, production, imports, centralized procurement, or digital coordination mechanisms can result in system-wide healthcare failures. It distinguishes between vertical critical nodes (e.g., single-source API suppliers, national warehouses, bottleneck manufacturing sites) and horizontal intersection points (e.g., hospitals, procurement bodies, and digital platforms for tracking and coordination). The analysis places special emphasis on achieving multi-tier (Tier N) supply chain visibility, developing integrated and interoperable digital infrastructures, diversifying sources of supply, fostering dynamic public-private cooperation, and building adaptive strategic reserves at national and institutional levels. The proposed framework integrates operational modeling with governance insights, offering a multidisciplinary methodology suitable for use in both developed and developing healthcare contexts. Ultimately, the study provides actionable tools for policymakers, logistics planners, and healthcare administrators to identify vulnerabilities, strengthen systemic preparedness, and ensure the continuity and quality of medical services under complex and uncertain conditions of crisis, war, or global disruption—especially in fragile economies or unstable geopolitical environments.

Keywords: supply chain mapping, supply chain resilience, healthcare, Ukraine.

JEL: I15, I18 M11

Introduction. Effective supply chain mapping and critical node identification are essential for strengthening resilience in the healthcare sector. This methodology involves creating a detailed map of the entire supply network – from raw material suppliers to end users – and pinpointing key "nodes" whose disruption would significantly impact the system [2]. In healthcare, supply chains are highly complex and increasingly international, often spanning multiple countries and stakeholders [24]. Recent crises such as the COVID 19 pandemic and Russia's invasion of Ukraine have starkly exposed vulnerabilities: unprecedented surges in demand combined with supply interruptions led to shortages of essential medicines, personal protective equipment (PPE), and devices [2, 3]. These challenges underscore the urgency of mapping healthcare supply chains end-to-end to improve transparency, anticipate risks, and identify critical dependencies.

Supply chain mapping in this context means visually and analytically tracing how health products flow from producers to patients, including all intermediate steps and actors. It requires gathering data on supplier locations, production sites, distribution centres, transport routes, and healthcare providers, as well as information flows and inventories. By doing so, stakeholders can gain "tier N" visibility – looking not just at direct suppliers but also sub-tiers – to reveal hidden choke points or single points of failure [39]. The critical nodes in a healthcare supply chain are those facilities or firms whose failure (e.g. a sole-source manufacturer, a major national distributor, a central warehouse or transport hub) would cause outsized disruption to healthcare delivery [2]. Mapping helps highlight such nodes so that contingency plans (such as alternative sourcing, strategic stockpiles, or redundancy) can be developed. As a report by the OECD notes, improving *"visibility…across the whole supply chain"* is a first step to better anticipate and avert shortages in both routine times and crises [16].

In applying supply chain mapping and critical node analysis to healthcare, it is crucial to account for the distinct characteristics of each major component of the sector. The healthcare sector encompasses multiple interrelated supply chains – pharmaceuticals, medical devices and equipment, medical consumables and supplies (including PPE), and even blood and blood products – each with its own structure and challenges. Below, we map the supply chain for each component, outline its specific features (with a focus on Ukraine's context and any global linkages), and identify critical nodes. For clarity, each component's supply chain is summarized in a table, followed by an integrated discussion of how these sub-chains interconnect within the overall health system.

Literature analysis. Recent research highlights that resilient healthcare supply chains are essential for uninterrupted patient care, especially under crisis conditions. For example, Arji et al. (2023) systematically reviewed 35 studies on COVID-19 supply chain disruptions and found that healthcare chains increasingly use technologies like AI, blockchain and big-data analytics to enhance resilience [31]. They noted that most work focused on planning for pandemic impacts and on the chains' vulnerabilities, but practical application of these emerging tools remains rare [31]. Likewise, Zamiela et al. (2022) conducted a U.S. case study using a multi-criteria decision-making (MCDM) approach to rank resilience enablers in medical supplies chains. Their analysis (informed by expert surveys) showed that redundancy, collaboration and robustness were the top indicators of a resilient healthcare supply chain, whereas factors like design or communication were relatively less critical during COVID-19 [17, 32]. Spieske et al. (2022) extended this European perspective with a multi-tier case study of nine medical suppliers and hospitals. Using resource-dependence theory, they found that "bridging" strategies (supplier collaboration and long-term partnerships) secured supplies more effectively than purely "buffering" (like extra stockpiles) in a pandemic; combining both approaches offered the best protection [33]. In summary, these global studies (and many others) emphasize sharing information, flexible sourcing partnerships and built-in slack as key resilience strategies.

Arji et al. (2023) – A systematic review of healthcare SC resilience strategies during COVID-19. Analyzed 35 papers, finding that AI, blockchain, big data and simulation are common tools for disruption management, but most research stays at planning stage [31]. Key finding: published work stresses vulnerability of healthcare chains and calls for stronger resilience methods, noting practical implementation is scarce.

Zamiela et al. (2022) – Case study of U.S. medical supply chains using the Proximity Indexed Value MCDM method. Interviewing healthcare experts, they ranked resilience factors for medical supplies. They identified redundancy, collaboration, and robustness as the most important enablers, while supply chain design and communication played smaller roles during COVID-19 [32].

Spieske et al. (2022) – European multi-tier case study (manufacturers and hospitals) on COVID-19 scarcity. Conducted 39 expert interviews and derived propositions for resilience. They found that bridging measures (e.g. joint planning with suppliers) were more effective for securing medicines than solely buffering measures; however, combining buffers (like shared inventories among hospitals) with collaboration gave superior risk mitigation [33]**.** Beyond qualitative factors, recent research applies network theory to pinpoint critical points in supply chains. Hua et al. (2025) propose a new method to identify critical nodes in any supply-chain network (SCN) by combining topological and functional indicators. Using a simulated underload-cascade failure model, they show this method effectively flags those enterprise nodes whose removal causes widespread disruption [34]. This provides an objective, quantitative means to evaluate node importance in a network. Other scholars have similarly used complex-network models and epidemic-like simulations to study how disruptions propagate through supply networks (e.g. Tang et al. 2021; Wang et al. 2024), underlining that certain suppliers or links can act as failure points that trigger cascading breakdowns. These works complement the more managerial studies by offering mathematical tools to rank node criticality.

Several studies focus on Europe (including recent crises) and on Ukraine specifically. Skowron-Grabowska et al. (2022) analyse a Polish case of interhospital medical air transport. Through a single-hospital case study and process mapping of 100 helicopter transfers, they identified factors affecting the reliability of this emergency SC. The key finding was that the coherent, integrated cooperation of all institutions (hospitals, dispatch, air rescue) was the principal factor ensuring reliable patient transfers [35]. Lebedeva & Shkuropadska (2024) examine transport logistics in Ukraine and the EU during war. They argue that wartime resilience hinges on intergovernmental coordination (in route planning, infrastructure, financing and regulation) and on flexible alternatives. Measures such as transparent logistics architecture, alternative delivery routes, strong partnerships and real-time monitoring are highlighted as critical for Ukraine's supply chains to withstand shocks [36]. These factors include customs efficiency, transport infrastructure quality, competitive pricing and cargo tracking as determinants of resilience.

In a policy-oriented perspective, Ukraine's Health Ministry (Liashko et al., 2024) emphasizes practical supply-chain reforms that helped weather war-related shortages. For instance, Ukraine partnered with private logistics firms for last-mile distribution (originally for HIV/TB drugs), then rapidly scaled this to cover other medicines, aided by digital inventory systems and mobile pharmacies [37]. The result, as one analysis notes, is that Ukraine's system has proven "extraordinarily resilient" in maintaining medicine access and affordability even under invasion. Complementary to these studies, OECD (2024) provides a global policy review: it reports that medical supply chains were already under strain before COVID-19 and that the pandemic worsened shortages of key drugs and equipment. The report recommends collaborative, cross-sector strategies to strengthen resilience for medical products, balancing private-sector innovation with public oversight [38].

Research methodology. This study applies a comprehensive healthcare supply chain mapping approach using structural-functional analysis and critical node identification. It is based on empirical data, a Ukrainian case study, and cross-sectoral comparisons of sub-chains (pharmaceuticals, medical equipment, consumables, and blood products).

The purpose of the article. The purpose of the article is to identify critical nodes within healthcare supply chains through full-spectrum mapping, in order to enhance system resilience and ensure continuity of medical services during crises.

The unresolved aspects of the general problem. Despite growing research on healthcare supply chain resilience, the systematic identification of critical nodes—particularly across interdependent sectors—remains insufficiently explored. Issues such as functional bottlenecks, geopolitical risks, and the lack of integrated data from overlapping sub-chains (e.g., pharmaceuticals, devices, blood supply) require a more applied methodology. The role of intersection points such as hospitals, logistics hubs, and digital platforms has also been underexamined. The Ukrainian experience under wartime conditions highlights the urgency of addressing these gaps.

Results. *Pharmaceutical Supply Chain Mapping and Critical Nodes.* The pharmaceutical supply chain covers the journey of medicines (including vaccines and other therapeutic products) from raw materials to patients. Ukraine's pharmaceutical sector illustrates the complexity of this chain, as well as its vulnerabilities and adaptations under stress. Table 1 outlines the key components of the pharma supply chain and their specific characteristics in the health sector context.

Table 1

PHARMACEUTICAL SUPPLY CHAIN COMPONENTS AND SPECIFICITY

Supply Chain Component	Specific Characteristics in Healthcare (Pharmaceuticals)
Raw materials & APIs	Active Pharmaceutical Ingredients (APIs) and other raw materials are the first link. Ukraine, like many countries, remains import-dependent for APIs – most are sourced from a few global producers (e.g. China, India). This high concentration of API manufacturing in a small number of sites presents a vulnerability: disruptions (natural disasters, geopolitical issues) in those regions can halt drug production worldwide. Local pharmaceutical companies rely on imported APIs for the majority of their production, reflecting a critical upstream dependency.
Manufacturing (Production)	Pharmaceutical manufacturing in Ukraine is a mix of domestic production and imported finished drugs. Domestic firms focus largely on generic medicines, constrained by financing and raw material supply issues. Not all local plants fully meet stringent Good Manufacturing Practice (GMP) standards, which can limit output or export potential. Import reliance is significant: even before the war, imports were nearly eight times larger than pharma exports. Local manufacturers account for about 65% of medicines sold by volume but only ~36% by value, indicating that higher-value patented or specialized drugs are mostly imported. This imbalance marks domestic manufacturing capacity (generics, lower-cost drugs) as a potential critical node – if imports are disrupted, local producers may not easily substitute high-tech or novel therapies. War impacts in 2022 further revealed manufacturing nodes at risk: some production facilities were damaged or fell in occupied territories, and foreign technical support became unavailable, forcing local teams to innovate to keep production running. Despite these challenges, major Ukrainian pharma companies like Farmak, Darnitsa, and Arterium maintained operations (some even continued production under bombardment or quickly resumed after initial shocks). Their resilience and rapid recovery were critical to preventing nationwide drug shortages, underscoring these manufacturers as critical nodes in the supply chain.
Distribution & Logistics	Pharmaceuticals typically flow through national wholesale distributors to pharmacies and hospitals. In Ukraine, there are hundreds of licensed distributors (401 as of 2020) and a vast network of approximately 17,485 pharmacies and 4,399 pharmacy points retailing medicines. However, the market is dominated by a few large distributor companies (critical nodes) that handle procurement and logistics for most of the sector (e.g. supplying both private pharmacies and public hospitals). The Medical Procurement of Ukraine (MPU) – a centralized state agency established in 2018 – has become a backbone for public sector drug supply. MPU consolidates government purchasing of essential medicines and medical supplies, achieving cost savings and faster delivery. This central procurement entity is itself a critical node: its effective functioning underpins medicine availability nationwide. During the war, MPU (with USAID SAFEMed support) rapidly adapted procurement and distribution processes to address disrupted supply lines. On the logistics side, transportation and storage are vital sub-nodes. The war highlighted risks here: in early 2022, closed ports and unsafe roads halted imports and internal deliveries of medicines, causing acute shortages in some regions. Alternative routes and humanitarian airlifts became essential to bypass blocked nodes. Large wholesale warehouses are also key nodes; the loss of a major warehouse (e.g. one

Supply Chain Component	Specific Characteristics in Healthcare (Pharmaceuticals)
	Ukrainian firm lost a warehouse containing its entire finished goods stock to destruction) can severely impact drug availability. Finally, the IT systems enabling visibility of stock (like Ukraine's MedData platform) are critical for logistics coordination; without them, it is hard to know where shortages are forming.
Dispensing & Use (End Users)	The end users of medicines are hospital patients and retail pharmacy customers. This stage in the chain is where healthcare outcomes are directly affected by upstream performance. Ukraine's experience during the war showed how demand shifts and access issues at the end-user level reverberate through the supply chain. In peacetime, hospitals account for only ~8% of pharmaceutical sales by value, with the bulk going through outpatient pharmacies. But in the initial months of the full-scale invasion, the hospital share spiked to ~40%, as emergency care and military medical needs surged while routine outpatient utilization fell. End-user access became a critical concern: in the first days of fighting, only about 10% of pharmacies were open, severely limiting public access to medicines. Yet this node proved resilient – within one month, 80% of pharmacies had reopened despite the conflict. Pharmacies' rapid restoration was crucial for getting medicines to patients, making them collectively a critical network node. Another end-use dynamic was the change in consumption patterns: Ukrainians stockpiled vital medications (leading to spikes in demand for drugs like insulin or blood pressure meds) while demand for non-essentials (vitamins, supplements) plummeted. Such shifts created imbalances – some pharmacies had overstock of low-demand items but shortages of lifesaving drugs. This highlights the need for agile demand monitoring at the end-user level, and that patients themselves are part of the supply chain, sometimes altering demand abruptly (a factor to map and anticipate).

Source: developed by the author, based on [2, 4, 5, 6, 8, 9, 10, 12, 15, 23, 24, 25]

Pharmaceutical critical nodes: From the above, critical nodes in the pharma supply chain include: *upstream API sources* (since lack of API halts all production) [4]; *major domestic manufacturers* (few companies producing a large share of essential generics); *central distributors/warehouses* (whose failure would collapse national distribution) [5]; and the *central procurement authority* (MPU) for Ukraine's public medicines supply [23]. Additionally, *transport infrastructure* (e.g. border crossings for imports, main logistics routes) proved to be critical nodes – e.g. the Western border crossings became bottlenecks when seaports were blocked [18, 20]. Strengthening pharma supply resilience thus involves diversifying API sources, holding strategic stocks of key medicines, ensuring backup distribution routes, and digital transparency of inventory at all levels [5, 14].

Medical Devices and Equipment Supply Chain Mapping. The supply chain for medical devices and equipment – ranging from simple syringes and gloves to complex imaging machines and ventilators – has a different profile. It involves a wide array of products with varying lifecycles, regulatory requirements, and degrees of local availability. Table 2 summarizes the components of the medical devices/equipment supply chain and their specific characteristics in the healthcare sector.

Table 2

MEDICAL DEVICES & EQUIPMENT SUPPLY CHAIN COMPONENTS AND SPECIFICITY

Supply Chain Component	Specific Characteristics in Healthcare (Medical Devices & Equipment)
Raw materials & Parts	Medical devices often require diverse raw materials and electronic components. For example, imaging equipment needs specialized metals, semiconductors, and software; disposables like syringes need medical-grade plastics. Many of these inputs are sourced globally. A notable risk is that certain critical components (e.g. semiconductor chips, specialized alloys) are also in demand by other industries. Competition for such inputs or trade restrictions can create bottlenecks. Additionally, some raw materials (like those for diagnostic reagents or PPE) saw supply shocks during COVID-19, illustrating their criticality. In Ukraine's case, local device manufacturers depend on imported components due to limited domestic materials production. This makes upstream suppliers (often abroad) key nodes – e.g. the global shortage of electronic components in 2021–2022 affected availability of monitors and ventilators in Ukraine, as in other countries.
Manufacturing (Production)	The medical device industry in Ukraine is relatively small, so most medical equipment is imported. In 2019, imports accounted for ~90% of total medical device sales in Ukraine. China, the USA, Germany, and Japan are among the largest supplier countries. Local manufacturing capacity exists (about 250 Ukrainian companies make some medical devices) but is limited to certain products – e.g. some radiological and ultrasound machines, orthopaedic prosthetics, simple hospital furniture and tools. The total local production of medical devices was only around USD 95 million in 2019, a fraction of the market. This indicates a heavy reliance on foreign manufacturers for everything from high-end diagnostic equipment to basic medical supplies. Critical nodes here are the major foreign manufacturers or sole suppliers of crucial equipment. For instance, if a single foreign company produces all replacement parts for a specific life-support machine used in Ukrainian hospitals, that company (and its supply line) is a critical node. Another critical node is regulatory compliance and quality control: devices must meet standards (CE marking, etc.) to be imported. Any disruption in regulatory processes (e.g. delayed approvals or new stricter EU regulations) can effectively choke off supply of devices (this was identified as a risk in the EU in vitro diagnostics regulation changes). During the war, production nodes included emergency local initiatives (e.g. Ukrainian firms 3D-printing medical device parts or ramping up PPE production) to compensate for import disruptions. Although ad-hoc, these efforts highlighted potential for local manufacturing to act as a backup node when global supply falters.
Distribution & Installation	Distributing medical devices often involves specialized handling, installation, and maintenance services. Import logistics are critical: with ~90% of devices imported, Ukraine's access depends on open trade channels and efficient customs clearance. The war exposed this vulnerability when border logistics were disrupted. Heavy equipment (MRI machines, CT scanners) typically arrives via seaports or large trucks – the port blockade in 2022 meant such shipments had to reroute via land borders, causing delays. Many devices also require installation by trained engineers; as an example, foreign engineers couldn't travel to Kyiv during heavy fighting to set up new production lines or equipment, forcing local teams to manage. Maintenance and spare parts supply chains are a further component: complex devices need a steady supply of spare parts and consumables (e.g. dialysis filters, imaging film or contrast agents). Those too are largely imported, and a failure in this sub-chain can render expensive machines unusable – making the service/parts providers critical nodes. Ukraine's healthcare system historically struggled with aging equipment in public facilities due to funding gaps. This meant dependence on periodic donor programs or centralized procurement for new equipment. The newly established National Health Service and reforms began addressing these needs (e.g. ambulances and angiography equipment funded in 2020). The Medical Procurement of Ukraine (MPU) also handles some device procurement for the state, similar to medicines, aggregating demand for items like stents or diagnostic equipment – again a critical coordination node. In summary, distribution relies on a chain of import agents, distributors, and technical specialists; any break (logistics delay, lack of installers, etc.) can delay patient access to technology.

Supply Chain Component	Specific Characteristics in Healthcare (Medical Devices & Equipment)
End Users (Healthcare providers)	The end users of medical devices are hospitals, clinics, laboratories, and patients (for personal devices). At this stage, the key concerns are availability, proper utilization, and interdependence with other supplies. A critical aspect is how device availability ties into healthcare delivery. For example, a functioning surgical suite depends on surgical instruments (devices), sterilizers, anaesthesia machines, etc., as well as medicines and blood. If any is missing, surgeries are postponed. Thus, a hospital is a nexus where multiple supply chains converge. In Ukraine, war damage to health facilities has been devastating: as of late 2024, over 1,550 medical facilities were damaged or destroyed, implying loss of equipment on a massive scale. This creates an urgent need to replace devices, making donations and emergency imports of medical equipment a lifeline (but also posing coordination challenges, as seen when overload of donated devices and medicines complicated inventory for local providers). Another factor is training and human resources – advanced equipment is only useful if healthcare workers know how to use and maintain it. Thus, from a systems view, teaching hospitals and biomedical engineering services are additional nodes to map. Specific critical nodes at the end-use stage include major referral hospitals (e.g. a key trauma hospital's oxygen plant or power supply for ventilators is a node whose failure endangers many lives). Additionally, in-home devices (like insulin pumps or oxygen concentrators for patients) became critical during conflict and pandemic lockdowns – supply chain mapping must extend to ensure patients outside hospital walls receive necessary devices and consumables.

Source: developed by the author, based on [2, 7, 9, 12, 13, 19, 22, 24, 41]

In the medical device supply chain, critical nodes are often the *points of high concentration or limited redundancy*: a single factory that produces a needed component, a sole authorized importer of a device, a central hospital storing life-saving equipment for a region, etc [28]. The war in Ukraine revealed that reliance on imports can be perilous if trade routes are cut – hence, border entry points and domestic distribution hubs emerged as critical nodes for device access [25]. Furthermore, maintenance/service providers for equipment constitute critical nodes; if they cannot function, devices in the field break down. Strengthening resilience here involves diversifying suppliers (both country-of-origin and vendor), stockpiling critical spare parts, and investing in local capacity for manufacturing or fixing equipment where feasible [3, 7].

Medical Supplies and Consumables Supply Chain Mapping. This category includes consumable medical supplies such as personal protective equipment (gloves, masks, gowns), syringes, IV fluids, reagents for labs, oxygen cylinders, and other expendable items. These supplies are the unsung backbone of daily healthcare delivery – a shortage of something as simple as a syringe or surgical glove can halt services. Table 3 delineates the supply chain components and specifics for medical consumables, highlighting the sector's particular issues.

Table 3

MEDICAL CONSUMABLES & PPE SUPPLY CHAIN COMPONENTS AND SPECIFICITY

Supply Chain Component	Specific Characteristics in Healthcare (Medical Devices & Equipment)
Raw Materials	Many consumables derive from commodity raw materials: plastics (for syringes, gloves), textiles (for gowns, masks), chemicals (for reagents, disinfectants), etc. These often have global supply chains tied to manufacturing hubs (e.g. latex for gloves from Southeast Asia, polypropylene for masks from China). Pre-pandemic supply chains were lean, with just-in-time production and low buffer stocks. This meant that when COVID-19 hit, raw material shortages quickly cascaded – e.g. lack of non-woven polypropylene material limited mask production worldwide. Additionally, quality standards for medical-grade materials add complexity; not any textile or plastic will suffice, and switching suppliers can be slow due to validation requirements. For Ukraine, most raw materials for consumables are imported, as domestic chemical and textile industries produce relatively little medical-grade input. Thus, a disruption in global commodity supply (such as a factory shutdown in China producing fabric for masks) is a critical upstream node that can affect the national availability of PPE.
Production (Manufacturing)	Production of consumables ranges from simple (mask sewing, saline solution filling) to moderately complex (PPE with multiple layers, specialized lab reagents). Historically, Ukraine imported a large share of its medical consumables. For example, before 2020, almost all high-quality PPE was imported; during the COVID-19 crisis, there were efforts to spur local manufacturing (e.g. Ukrainian garment factories repurposed to make masks, or distilleries producing antiseptics). These efforts somewhat increased domestic supply, but quality and scale remained challenges. Globally, manufacturing of items like gloves is concentrated (e.g. Malaysia for latex gloves), which is a risk if that node fails. In supply chain mapping, each major supplier factory is a node – the pandemic taught that lack of multiple suppliers for critical consumables is dangerous. A case in point: a single factory's shutdown can cause worldwide shortages of something as basic as a test swab. Ukraine's strategy has been to diversify procurement (multiple countries, international organizations) to avoid over-reliance on one source. Nonetheless, the critical nodes in manufacturing are those limited-source items (for instance, a particular reagent only made by one or two companies, or a specific vaccine syringe with few producers). Identifying these in advance allows for contingency stockpiling or encouraging alternative suppliers.
Distribution & Inventory	Consumables typically flow through distributors to end users, similar to medicines, though often via separate channels (especially for public health supplies). An important characteristic is the fast turnover and volume of these items – hospitals can use thousands of gloves or litres of oxygen per day. Thus, inventory management is crucial. Prior to COVID-19, many healthcare systems used just-in-time (JIT) inventory practices to minimize holding costs. However, COVID demonstrated that JIT, without buffers, "amplifies the risk of medical product shortages" and can endanger patient care. In Ukraine, the war and pandemic forced a pivot to holding strategic reserves of key supplies (e.g. emergency stockpiles of PPE and oxygen) to cushion against supply shocks. That said, stockpiling has drawbacks: consumables can expire. Studies found that in some settings a significant share (on the order of 10–15%) of stocked items expired unused. Optimal strategy has become a hybrid: maintain a baseline buffer of essentials while still relying on regular replenishment for most needs. Distribution-wise, central medical stores (warehouses) and cold chain logistics for temperature-sensitive supplies (like certain reagents or vaccines, which fall under consumables) are critical nodes. If a central warehouse is destroyed (as happened to one major pharma distributor's warehouse in 2022) or if electricity for cold storage fails, large quantities of supplies can be lost. During the invasion, Ukraine's logistics partners had to work around damaged roads and closed airports to deliver supplies– making alternate routes and decentralized stock locations vital. Indeed, humanitarian convoys and regional hubs became part of the supply chain, adding nodes to the network that had to be managed.

Supply Chain Component	Specific Characteristics in Healthcare (Medical Devices & Equipment)
End Use (Healthcare Delivery)	The end users for consumables are hospitals, clinics, labs, and ultimately patients. This is where supply meets demand in immediate, life-saving ways. The criticality of this stage is obvious: without PPE, health workers are at risk; without syringes, vaccinations or treatments cannot be administered; without oxygen, critical patients may not survive. In Ukraine's war context, certain supplies gained outsized importance – for instance, blood bags, tourniquets, and wound dressings became as strategically important as any weapon, needed to treat mass casualties. Ensuring these are in the right place at the right time required mapping not only the supply sources but also demand hotspots (front-line hospitals, field clinics). One challenge was that some regions experienced acute shortages while others (especially early on with massive external donations) had oversupply that risked expiry. MedData and other tracking systems were extended to consumables, enabling the Ministry of Health to see stock levels of critical items across thousands of facilities. This real-time visibility helped redistribute supplies to where they were most needed. It exemplifies how end-use data is a crucial part of supply chain mapping – essentially feeding back into procurement decisions. At the patient level, some consumables became scarce or rationed (for example, insulin syringes or test strips for diabetics in war-torn areas). NGOs and volunteers became supplementary nodes, hand-delivering such items to patients isolated by fighting. Thus, in mapping the full picture, non-traditional last-mile nodes (volunteer networks, military medical units) must be included during crises. The end stage is also where waste management of used consumables occurs (e.g. safe disposal of sharps, biomedical waste), which, while a public health issue, can circle back – disruptions in disposal could block new supplies if facilities are overfilled with waste. While not traditionally seen as part of the supply "chain," a holistic mapping might note it to ensure sustainability and safety throughout the supply cycle.

Source: developed by the author, based on [2, 3, 6, 9, 12, 19, 26]

For consumables, critical nodes identified include: large PPE or reagent manufacturers (global nodes that if they fail, many countries suffer); national warehouses and distribution fleets; and the stock monitoring systems that trigger resupply. The balance between JIT and stockpiling is itself a strategic node – too little inventory is risky; too much can lead to waste [3]. Therefore, agile supply chain management, informed by mapping, is needed to adjust inventory policies dynamically based on risk. The pandemic revealed that better international coordination is needed as well: export restrictions by some countries on PPE acted as critical throttling nodes that worsened global shortages [2]. In response, countries like Ukraine diversified import sources and local production for critical supplies (e.g. multiple international donors and suppliers were engaged for COVID vaccine syringes, alleviating dependence on a single source). Mapping these interdependencies in advance allows health authorities to identify where a single supplier or country controls a large share of supply – a clear signal of a critical node that merits mitigation (through alternate suppliers or stockpiles).

Blood and Blood Products Supply Chain Mapping. An often-overlooked but vital component of the health sector supply chain is blood and blood products (such as red blood cell units, plasma for transfusion, platelets, and plasma-derived medicines). The blood supply chain is unique in that its "raw material" is human donations, and it has a very limited shelf life and strict cold chain requirements. In Ukraine, the war dramatically underscored the importance of mapping and strengthening this supply chain. Table 4 outlines the blood supply chain components and their specifics.

Table 4

BLOOD AND BLOOD PRODUCTS SUPPLY CHAIN COMPONENTS AND SPECIFICITY

Supply Chain Component	**Specific Characteristics in Healthcare (Medical Devices & Equipment)**
Donation (Collection)	Blood supply begins with donors – volunteers who give whole blood or blood components. This supply chain component is fundamentally local (one cannot import fresh blood easily due to time constraints and cross-matching requirements). In peacetime, Ukraine's blood collection operated via regional blood centers and periodic donor drives. A critical factor is donor mobilization: during crises, donation surges or drop-offs can occur. For instance, at the war's outbreak, many civilians rushed to donate blood for wounded soldiers, but in areas of heavy fighting, donation became difficult or dangerous. Mapping donation sites and their capacity is crucial. The critical nodes here are the major blood centers in each region, as well as mobile collection units. If a large blood center (say in Kyiv or Kharkiv) is damaged or without power, the region's collection ability plummets. The war led to some blood centers relocating or operating under emergency conditions. Ensuring generators and supplies (needles, bags, test kits) for blood collection is part of the supply chain – these inputs overlap with the consumables chain (another interdependency).
Processing & Testing	After collection, blood units must be tested, typed, and processed (separated into components like plasma, platelets, etc.). This happens at blood centers or transfusion laboratories. These facilities require specialized reagents and equipment (for disease screening, blood typing, etc.), which ties the blood supply chain to the medical lab supply chain (e.g. test kits for HIV/Hepatitis screening are typically imported, making them critical sub-nodes). In Ukraine, each regional blood center generally handles processing for that region. A critical node is the central reference laboratory that may confirm tests or handle rare blood units. During conflict, maintaining cold chain and laboratory function (despite infrastructure damage) is vital – if power is lost, blood stock spoils. Some Ukrainian blood centers faced such issues in 2022, prompting use of generators and relocation of stocks. Mapping these facilities and their backup systems (generators, reagent suppliers) was necessary to ensure continuity. Additionally, plasma-derived medicinal products (like clotting factors or immunoglobulins) depend on plasma collection and shipment to fractionation plants (usually abroad, since plasma fractionation is not done in Ukraine). This introduces an international node: agreements with foreign fractionators and the logistics of exporting plasma and re-importing finished products. Any break in that link (e.g. border closures or loss of air freight capacity) can lead to shortages of critical medicines for hemophiliacs, etc.
Storage & Distribution	Blood is perishable (red cells ~35–42 days, platelets ~5–7 days, plasma frozen but needs cold storage). Thus, inventory management and distribution are extremely time sensitive. Ukraine's challenge has been to keep an updated picture of blood inventories across the country, especially as the war caused uneven demand – frontline hospitals in the east/south might face mass casualty events requiring large volumes, while other areas might have unused surplus. A digital tracking system is crucial for this component. Indeed, Ukraine rapidly worked to integrate blood supply data into its national MedData platform in 2022. Before this, there was "no real understanding of what was going on with the blood supply" nationally – a dangerous blind spot. Now, with data from blood centers and hospitals on stock levels, the Ministry of Health can identify shortages and direct redistribution of units as needed. This real-time visibility effectively maps out the blood supply chain in motion. Critical nodes in distribution include the transport links (blood must be transported under refrigeration; if roads are blocked or fuel is unavailable, that's a choke point)

Supply Chain Component	Specific Characteristics in Healthcare (Medical Devices & Equipment)
	and regional blood coordinators who decide how to allocate units. During intense battles, the coordination to move blood from west Ukraine (where donation was higher and hospitals less burdened) to eastern front-line hospitals became a lifesaving logistics operation. Planes, trains, and military convoys have all been used as part of the distribution network – adding complexity to mapping, as military medical logistics had to interface with civilian healthcare. Each mode of transport and trans-shipment point (e.g. a railway hub where blood coolers are transferred) can be viewed as a node that must function properly.
Transfusion (End Use)	The final step is the transfusion to patients in hospitals or field clinics. At this point, the concerns are having the right type of blood at the right time. If any earlier node fails (no donor, no test kits, no transport), the bed at the hospital where a patient's bleed cannot be saved. Hospitals usually keep a buffer stock of common blood types, but for large-scale needs they rely on the wider network. Critical nodes at end use are the major transfusion centers (hospitals) especially trauma centers that handle many transfusions. Their blood bank refrigerators and staff capacity (to perform compatibility testing and transfusions rapidly) are crucial. War has effectively made every hospital a potential trauma center, increasing strain on all. Another aspect is blood substitutes or alternatives (like saline fluids for initial resuscitation, or synthetic volume expanders) – these are part of the medical supply chain that supplements blood usage. If blood is low, these items (which come from pharmaceutical supply chains) become critical. Thus, the blood chain's end use ties back into pharmaceuticals and consumables (illustrating interdependence). Post-transfusion, monitoring and adverse event reporting (if a patient has a reaction) loop back into quality control in the supply chain, ensuring future safety.

Source: developed by the author, based on [5, 6, 12, 29]

In the blood supply chain, critical nodes include: major regional blood centres (each a hub whose impairment can isolate a whole area's blood supply), the national blood stock information system (a digital node providing visibility), and the transport corridors linking blood supplies to demand centres. During the war, an example of critical node fortification was the rapid development of the digital blood tracking module within weeks, which allowed prioritized distribution to areas "hardest hit by the war with the most acute needs" [3]. This demonstrates how identifying an information gap as a critical node – in this case, lack of data was itself a vulnerability – led to a solution that strengthened the entire blood supply chain. Additionally, integration with international partners for blood products (plasma fractionation, rare blood type exchange) implies that those external connections are also critical nodes to be managed via agreements and contingency plans.

Discussion. Integrating Sub-Supply Chains: Sector-Wide System Mapping and Dependencies. While we have discussed pharmaceuticals, medical devices, consumables, and blood separately, in reality these sub-supply chains operate interdependently within the healthcare system. A key part of the methodology is to map not only each chain, but also the linkages between them, to understand how a disruption in one can impact the others and overall health service delivery. The entire health sector's supply network can be visualized as an interconnected web, where nodes often intersect or rely on common infrastructure. For example, a hospital is a nexus that depends on all supply chains – medicines, devices, supplies, and blood. If the pharmaceutical supply is disrupted (say essential antibiotics are missing), surgical procedures (which also require sterile supplies and working equipment) may be canceled despite having all other inputs. Conversely, if a critical device (like an MRI or oxygen generator) is down, patient care suffers even if medicines are available. Thus, mapping dependencies is as important as mapping the individual chains.

Several dependencies and integration points emerge from the above analysis:

- Shared Infrastructure and Logistics: All supply chain components often share the same transportation networks (roads, rail, air) and storage facilities. A single transport disruption (like the closure of an airport or a major highway) can simultaneously delay drug shipments, device deliveries, and distribution of PPE. In Ukraine, when airports closed due to war, both medicine imports and relief shipments of medical equipment had to reroute through land borders [9]. This created a systemic bottleneck. Supply chain mapping therefore considers certain infrastructure nodes (ports, border checkpoints, main warehouses) as critical across multiple chains. Protecting or finding alternatives for these nodes (e.g. establishing additional logistics hubs in different regions or neighbouring countries) increases resilience sector-wide [2].
- Common Suppliers and Manufacturing Links: Some suppliers provide products for multiple chains. For instance, a chemical plant might produce raw materials for pharmaceuticals and also reagents for diagnostic kits. If that plant goes offline, it hits both the pharma chain and the consumables chain for labs. Similarly, a power outage in a region can halt a pharmaceutical factory and a PPE factory at once. Mapping needs to identify such single points of failure that straddle several supply categories. In practice, Ukraine's import dependence meant that disruptions in major exporting countries (e.g. India's lockdown affecting medicine export, or China's factory shutdown affecting PPE) had multi-chain impacts [2]. Thus, diversifying and securing supply lines is a cross-cutting strategy – it's not enough to have backup for drug suppliers if all PPE comes from one source, and vice versa.
- Interchangeability and Trade-offs: In crisis situations, shortages in one area force substitution from another. A clear example is blood vs. IV fluids: if blood is scarce, doctors might use more IV fluids (which come from pharma supply) to stabilize patients. Or if a specific device is unavailable (say a particular catheter), clinicians might improvise with a different device or drug. However, these substitutions have limits. Mapping should include where such interfaces and trade-offs exist, as they represent pressure valves or additional failure modes. During COVID-19, when ventilators (device) were in short supply, the focus shifted to high-flow oxygen therapy (consumable resource) and certain drugs for respiratory support [2]. A resilient system had to boost oxygen supply (tapping the industrial gas supply chain) while awaiting more ventilators – showing how chains interlink. In Ukraine's war, when standard supply routes for medicines were disrupted, humanitarian aid (an external supply chain) filled the gap, though it inadvertently crowded out local pharma sales in some segments [11]. Mapping these external auxiliary supply lines (military medical supply, international aid) and how they integrate with regular channels is crucial in a comprehensive sector map.

- Central Coordination Nodes: At the sector level, certain entities coordinate multiple supply chains. The Ministry of Health, for example, oversees policies affecting pharma, devices, supplies, and blood. In Ukraine, the Medical Procurement of Ukraine (MPU) and the National Health Service (NHSU) play coordinating roles: MPU handles procurement of both medicines and many medical devices/supplies for hospitals [3], and NHSU's financing can influence what hospitals purchase across all categories [7]. These bodies are critical nodes because they integrate information and decision-making across the sub-chains. If coordination fails (say, procurement focuses on medicines but neglects corresponding supplies), the system can experience mismatches (like having vaccines but no syringes). The importance of integrated planning is evident in Ukraine's approach to reform: state programs try to bundle resources (e.g. the Medical Guarantees Program covers certain medications and services together [21]). The supply chain mapping exercise at the national level should therefore involve these central nodes to ensure all components fit into a unified strategy.
- Information Systems and Data Sharing: A recurring theme is the need for visibility across all supply chains. A modern health supply chain management system aggregates data on drug stocks, equipment status, consumables levels, and blood availability. Ukraine's digitization efforts (e.g. eHealth system, MedData, etc.) were fortuitous investments that paid off in wartime [30]. They allowed leadership to *"track medicines and medical supplies from the warehouse to the hospital and ultimately to patients"* [30] and extended to blood tracking [29]. Such systems serve as integrative maps of the sector. They highlight dependencies (for instance, if a certain region consistently reports low stocks of various items, it might indicate a logistics breakdown in that area – a node requiring attention). Enhancing data-sharing between different supply chain stakeholders – pharmacies, hospital logistic units, blood centres, donors, international suppliers – is crucial for a holistic map. Indeed, regulators often lack upstream supply chain information and rely on industry to report issues, which is insufficient [27]. By connecting the dots via data, critical nodes and weak links become apparent in real time. This is why supply chain mapping is not a one-off project but an ongoing, dynamic process, continually updated with data feeds from all components [1].

In summary, the entire healthcare sector's supply chain system functions as an integrated network of interdependent sub-chains. A failure in one area (a critical node) can trigger cascading effects on others. For example, if a major distributor's warehouse burns down, it's not just medicines that might be in that warehouse, but possibly some consumables and small equipment too – affecting multiple categories. Or consider a regional crisis: if conflict isolates a region, that region's hospitals will lack drugs, supplies, equipment maintenance, and blood – all at once. The mapping methodology, therefore, must encompass the big picture, identifying not only vertical critical nodes (within one supply chain) but also horizontal nodes that connect chains (like shared logistics or funding mechanisms).

Conclusions. Ukraine's experience through reform, pandemic, and war provides a compelling use-case for this holistic approach. The country's focus on centralizing and digitizing supply management created tools that were, in effect, supply chain maps used actively to respond to crises [6, 30]. The war then stress-tested every link, revealing where mappings were accurate and where surprises occurred (such as the overwhelming influx of humanitarian aid acting as a parallel supply chain requiring management [19]). Lessons learned include the value of having multiple suppliers and donors (source diversification) [3], maintaining emergency inventories for critical items despite JIT temptations [26], investing in local production where feasible (to reduce sole reliance on imports), and enhancing cross-sector coordination (military-civilian, public-private partnerships) for health logistics [17].

In conclusion, mapping the health sector's supply chains and identifying critical nodes – across pharmaceuticals, devices, consumables, and blood – enables stakeholders to visualize the entire ecosystem of healthcare delivery. It illuminates how each component fits into a unified system and what dependencies exist between them. Such clarity is the foundation for risk mitigation strategies: strengthening or adding redundancy to critical nodes, developing contingency plans for their failure, and ensuring that all sub-systems can support each other. As the OECD report on medical supply chains emphasizes, "reliable medical supply chains are a cornerstone of resilient health systems", and achieving that reliability requires collaborative approaches that span private sector, government, and international partnersoecd.orgoecd.org. By employing thorough supply chain mapping and critical node analysis for each part of the health sector, countries can build a more robust, adaptive, and integrated healthcare supply network – one that can withstand shocks and continue to deliver lifesaving goods and services to the population.

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