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MATCH 2.0: A New Ledger for Nonproliferation

Using Distributed Ledger Technology to resolve chemical trade discrepancies under the Chemical Weapons Convention

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Every year, States Parties to the Chemical Weapons Convention declare to the Organisation for the Prohibition of Chemical Weapons their trade in dual-use chemicals—substances with legitimate industrial uses that can also be weaponized. Yet year after year, these declarations don't add up. In reporting for 2023, three-quarters of declared dual-use chemical transfers had discrepancies, representing a risk that some chemicals are unaccounted for and could potentially have been diverted for use as chemical weapons.

MATCH 2.0 explores a bold solution: can blockchain-style technology help nonproliferation stakeholders spot and fix these errors before they become risks? Through real-world testing, MATCH 2.0 shows how Distributed Ledger Technology (DLT) could help strengthen trust and transparency while preventing the reemergence of chemical weapons.

EXECUTIVE SUMMARY

For nearly four years, the Monitoring and Tracking Chemicals project (MATCH) has acted as an incubator for testing distributed ledger technology (DLT) to identify, resolve, and reconcile chemical trade reporting discrepancies in the reporting of the global trade of chemicals covered by the Chemical Weapons Convention (CWC).

A phased approach to testing and socializing DLT and the MATCH platform were key to its success, bringing National Authorities (NA), industry, the Organisation for the Prohibition of Chemical Weapons and tech developers together to share concerns,

benefits, behavioral insights and understanding of institutional capabilities. Over time, this approach has developed an informed user base and closed the gap between a key emerging technology and real-world implementation.

INTRODUCTION

The Chemical Weapons Convention (CWC) is the world's first international treaty that verifiably bans an entire category of weapons of mass destruction. Negotiated over four decades in the last century, the Convention and its implementing body, the Organisation for the Prohibition of Chemical Weapons (OPCW), have come of age this century – marking 28 years in April 2025. This time span also marks the rise of the digital age and the rapid emergence and convergence of advanced technologies such as artificial intelligence, advanced manufacturing, and distributed ledger technology. To prevent the re-emergence of chemical weapons, the OPCW must navigate the pace of a changing threat landscape while leveraging innovative technologies to enhance implementation and verification. However, the path to technological adoption is rarely straightforward. International organizations often struggle with slow decision-making, regulatory uncertainties, cybersecurity concerns, and the challenge of integrating new systems into existing frameworks.

Since its kick-off meeting in September 2021, the Stimson Center has coordinated closely with the OPCW on the MATCH project to understand the feasibility of DLT as an innovation for strengthening the annual declarations process for international transfers of chemicals covered by the CWC's "Schedules of Chemicals." These "scheduled chemicals" represent a small subset of the global annual trade in chemicals and have many legitimate medical, commercial and industrial uses, but also pose the highest risk of chemical weapons use. Every year, all 193 States Parties to the CWC must declare to the OPCW the aggregate quantities of scheduled chemicals traded above prescribed thresholds. And every year the occurrence of discrepancies in annual declarations remains high. In many cases, the books are never fully balanced, and transfer discrepancies remain unresolved, raising a risk that unaccounted quantities of dual-use chemicals might be diverted for weaponization. These challenges raised the question: what if all parties were connected on a single ledger? Would reconciliation work more efficiently? What if discrepancies could be identified and reconciled before reports went to national authorities? Would distributed ledger technology help?

With funding from Global Affairs Canada, MATCH has taken a step-by-step approach to answering these questions through several phases of research, scenario building, and testing of DLT, first through MATCH 1.0 (2021 – 2023) and most recently through a follow-on phase of the project, MATCH 2.0 (2023 – 2025). The results indicate not only that DLT can make reporting of aggregate transfer volumes more streamlined and efficient, but that it can also flag discrepancies early on so that transaction

counterparties can resolve them, avoiding higher level reporting discrepancies altogether. MATCH also provided insights into the adoption of innovative technology and the institutionalization of a new technology by an international organization.

THE TRANSFER DISCREPANCY PROBLEM

Overall, only a small subset of the global annual trade in chemicals is covered by the CWC, specifically those substances that pose the highest risk of chemical weapons use, referred to as "scheduled chemicals." Schedule 1 chemicals are those defined by the CWC (Article II) that have been developed, produced, stockpiled or used as a chemical weapon (CW). They are strictly governed, and only small amounts are transferred for research, medical, pharmaceutical, or protective purposes with advance notice to the OPCW and are thus easily matched. Transfer discrepancies, therefore, are specific to Schedule 2 and 3 chemicals. Schedule 2 chemicals are highly toxic or precursors that have significant risk for CW use while Schedule 3 chemicals are also potentially toxic and could be used as chemical weapons if diverted but are produced in large quantities for legitimate commercial purposes. In 2023, the total amount of declared transfers of Schedule 2 and 3 chemicals was 578,647 metric tons. A very small portion (less than 2%) were Schedule 2 transfers (see Table 1).

Table 1. Amount of total declared trade of scheduled chemicals (metric tons)[1]

	2019	2020	2021	2022	2023
S2 chemicals	11,650	12,211	6,466	6,283	9,336
S3 chemicals	528,186	433,258	413,133	539,577	569,311

The Convention requires National Authorities (NAs) to declare the aggregate annual totals of Schedule 2 and 3 chemicals traded with other countries above certain quantity and concentration thresholds (defined in the CWC and by decisions of the Conference of the States Parties). Every year, industry reports aggregate imports and experts of each Schedule 2 and 3 chemical and country of origin/destination to their NAs. NAs in turn further aggregate the reports (by chemical and country) and declare them to the OPCW, where the Technical Secretariat compares declared exports and imports of each chemical by country and identifies any discrepancies.

According to the OPCW, in 2023, 75% of transfers of Schedule 2 and 3 chemicals above the declaration threshold showed discrepancies.[2] In addition, the Stimson Center research team reviewed the OPCW's Annual Reports for the past several years to establish the scope of the transfer discrepancy (TD) challenge. Table 2, below, shows a steady rate of transfer discrepancies over this period.

Table 2. Percentage of transfers declared above the declaration threshold that showed discrepancies (2017-2023)[3]

Year of scheduled chemical transfers	2017	2018	2019	2020	2021	2022	2023
% of transfers declared above the declaration threshold showing discrepancies	66%	69%	71%	74%	74%	71%	75%

NAs submit their declarations in the first quarter of the year for the previous year's trade, in some cases relying on the submission of industry reports on their trade in scheduled chemicals, and in others relying on export license and permit data to make their declarations. The OPCW notifies NAs of the transfer discrepancies (TDs) between each countries' reports in the summer, and NAs in turn begin working with their NA counterparts and domestic industry to reconcile inconsistencies. Once notified, NAs navigate a variety of formal and informal channels with their counterparts in other countries and their own domestic industry to try to reconcile the discrepancies, a labor-intensive process that can require diplomatic coordination that can take several months to more than a year to resolve.

During MATCH 2.0, Stimson engaged a total of 23 organizations, including the OPCW, NAs, and industry organizations and learned more about national systems of CWC implementation and different causes of TDs. As noted in previous reports, clerical errors such as misplaced decimal points and incorrectly entered unique identification numbers called CAS Registry Numbers™ which frequently cause TDs for NAs. Another key issue is the lack of standardization of regulatory and declarations requirements for chemical industry across different countries. Inconsistent CWC implementation among States Parties takes multiple forms, from applying concentration or quantity reporting threshold requirements to industry that are different to those set by the OPCW for NA declarations, to the use of rounding rules that are different to OPCW guidelines.

Several NAs mentioned that a top cause of transfer discrepancies is industry misidentifying or not reporting a scheduled chemical in a mixture. Two of the most frequently traded Schedule 2 chemicals often found in mixtures are methyl phosphonates such as methylphosphonic acid compound with (aminoiminomethyl) urea (CAS RN 41203-81-0) and CAS RN 42595-45-9 (Antiblaze 1045). They are flame retardants also used commonly in plastics and textiles and contain a mixture of chemicals, only one of which is covered by the CWC's Schedule 2.

Customs unions also present a unique set of issues as national customs regulations do not treat chemical transfers within the borders of the union as international transfers, while the CWC does. As a result, some smaller or less experienced chemical companies may not report these transfers to the relevant NA. NAs also identified "back-to-back transfers," which can involve multiple countries, as a significant cause of transfer discrepancies, resulting from some companies reporting imports and exports based on the location of parties to the relevant contracts, financial flows, or transit countries, rather than on the physical origin and destination of the goods, as required by the OPCW Declarations Handbook. For other NAs that base declarations to the OPCW on permits issued, shipments cancelled after permits are granted present reporting headaches as the cancellations are not always recorded and are therefore difficult to track.

Many issues can be addressed by increasing awareness within the chemical industry about how to identify a scheduled chemical (particularly when in a mixture) and the need to report international transfers of scheduled chemicals to NAs (and the OPCW) even when they are traded within a customs union and do not need customs clearance. The OPCW's two regional workshops in 2024 on TDs, one in Seoul and the other in Madrid, have helped to raise awareness about the causes of discrepancies among NAs. The Stimson research team observed a noted difference in NA awareness between the first phase of the project (MATCH 1.0) and the second (MATCH 2.0), particularly among NAs in Asia and Europe. Awareness of the causes among NAs and industry is key to minimizing TDs and it is the responsibility of NAs to inform their domestic industry.

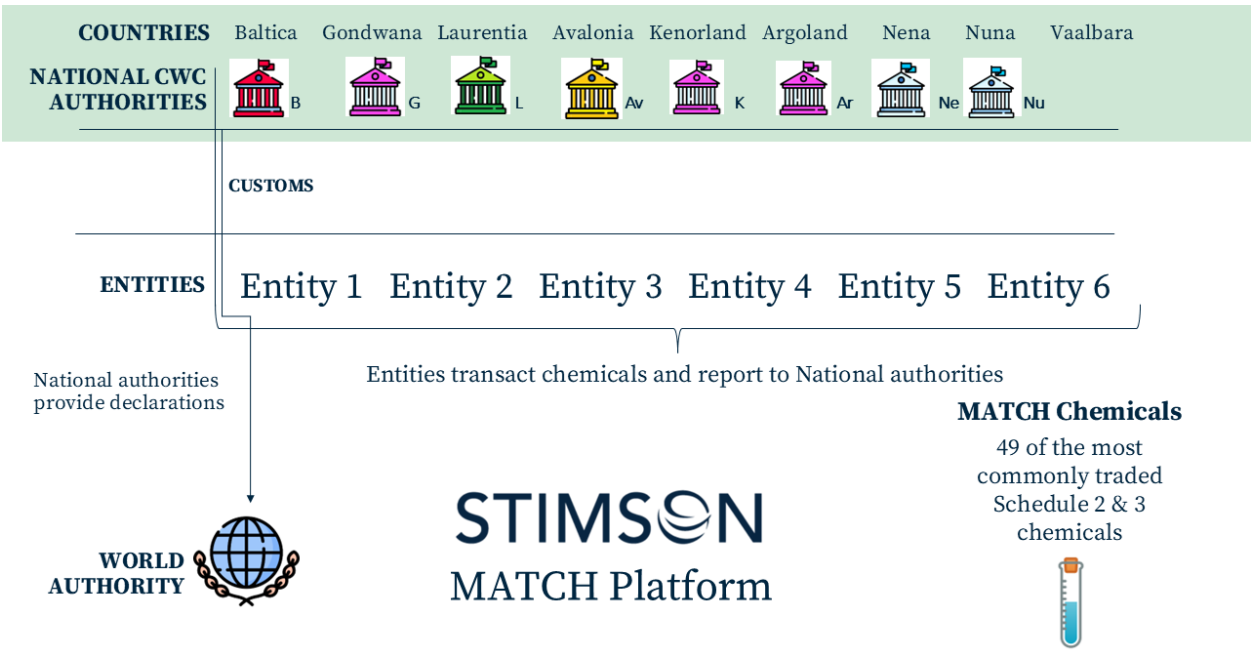
At the same time, the relationship between NAs and industry also varies across States Parties due to different CWC implementing legislation. Stimson observed that in countries where the customs authority is the NA, the relationship with industry is not only closer, but also allows the NA to directly access import and export declarations to crosscheck industry-reported country of origin, country of destination, and other relevant data. Some NAs are responsible for the licensing process specifically for trading scheduled chemicals and can therefore compare permits with industry reports. Stimson also met with NAs that have data-sharing agreements to access customs data while other NAs remarked that customs is a "black box" and they have no access or, in some cases, vague or incomplete guidance in legislation on how NAs should engage with their customs authorities and industry. In one State Party engaged in MATCH, the NA is a chemical industry association. This was a unique situation, however, as many NAs are limited by laws and regulations designed to prevent disclosure of confidential business information that in turn hampers direct engagement between NAs and their domestic chemical industry. In some countries with smaller industries, Stimson observed that there was little understanding by NAs about their domestic industry and the volume of scheduled chemicals traded.

Relationships and communication between NAs are also important to the reconciliation process. The diplomatic routing from one NA to other NAs can be tedious and slow, and in some cases no response is ever received. NAs that have the authority to establish direct connections with their counterparts and manage to do so have a smoother, more timely process. When an NA is called on to resolve a transfer discrepancy with a country that represents a new or infrequent trading partner, there can be difficulties in even identifying the NA counterpart and tracking down their contact information.

THE APPROACH AND FINDINGS

To test DLT as a solution to these issues, MATCH used a fictional "ecosystem" of notional States Parties, genericized chemical industry entities, and a central "World Authority" as the collection point for annual aggregate reporting of international transfers. In MATCH 1.0, the fictional ecosystem consisted of just five states parties, six entities, one World Authority and four scheduled chemicals. "Entities" broadly represent the chemical industry, whether manufacturers or distributors. For MATCH 2.0, the Stimson Center research team scaled up the fictional ecosystem to encompass 49 of the most traded Schedule 2 and 3 chemicals and a larger number and broader variety of system participants (including a Customs Authority and a non-State Party to the CWC) and a wider range of scenarios for testing. A fictional ecosystem allowed an "incubator" approach for industry, NAs and the OPCW to engage with the platform and test it without using sensitive information. Testers logged into the platform via a URL as "entities", NAs, or the OPCW to see how the platform works at each stakeholder level and could follow scenarios that Stimson designed or their own test cases. The MATCH 2.0 ecosystem is outlined in Figure 1.

Figure 1. MATCH 2.0 Ecosystem



Stimson also worked closely with its two developers throughout the project. DataTrails provided the DLT backbone of MATCH and True North, a software services company, built MATCH's intuitive user interface to reduce the friction of manual processes, automating as much as possible to create a user-friendly experience. The team developed a series of use cases that mapped to a workflow expected in a real-world operation for stakeholders to test within the MATCH ecosystem.

Working within this closed and simplified fictional world, both MATCH 1.0 and 2.0 have demonstrated how a DLT platform could simplify and streamline this extremely complex real-world system by connecting all participants on a single authoritative "ledger." This connection, in turn, would allow those at the root of the reporting chain, the chemical companies who make the transfers of scheduled chemicals, to eliminate many sources of discrepancies and address others before reaching the reporting chain. MATCH allows chemical industry entities to share transaction information in the system, reducing the incidence of clerical errors. When discrepancies between the two sides of a transaction are recorded in the system, MATCH 2.0 (like its earlier prototype) flags those discrepancies. To reconcile differences in recorded export and import quantities when warranted, the platform allows industry entities to append revised data—a standard DLT practice—without altering the original submission, thus ensuring a transparent audit trail while reducing incidences of discrepancies being aggregated into the national reporting chain. Further benefits of the MATCH system for both industry and NAs are the platform's ability to reconcile different units of measurement and different methods of reporting concentration level and to automatically generate aggregated annual reports or declarations. The reports successfully differentiate between each Schedule 2 and 3 chemicals transferred, and the source and destination countries of each transfer, as required by the OPCW.

While a real-world DLT platform would not overcome all causes of transfer discrepancies (see later sections of this report) nor remove the need for NAs to communicate, it would help their communication by providing an authoritative audit trail that enables industry to locate specific transactions and their trade details more quickly and efficiently.

NEXT GENERATION MATCH

DLT is a broad category encompassing various decentralized ledger technologies. The MATCH project has tested two different types of DLT systems. MATCH 1.0 was developed using Hyperledger Besu, a flexible and widely accessible Ethereum-based blockchain platform that allowed building in permissioned access controls. For MATCH 2.0, Stimson worked closely with DataTrails, a DLT developer, and True North, a software developer, to design and build the platform using Forestrie, DataTrails' patented high performance, scalable DLT. Forestrie is designed for sophisticated supply

chains requiring increased transparency and security while allowing third party verification.

Hyperledger Besu minimized environmental impact compared to other blockchain solutions because of the platform's capability to implement a Proof-of-Authority consensus mechanism, as opposed to popular alternatives, such as Proof-of-Work and Proof-of-Stake, which are more energy-intensive.[4] Consensus mechanisms offer automated distributed database management to ensure data is not changed. They are used in DLT systems to achieve agreement about the state of the data set on the ledger and replace the inaccuracies and unreliability of human verifiers and auditors while addressing data tampering and unauthorized access – malicious or not. Encryption algorithms create long strings of alphanumeric numbers, called a "hash", which are verified by the network's programs and only changed if the hashing algorithm is changed, and therefore programs running on the network are designed to compare hashes and ensure they match.

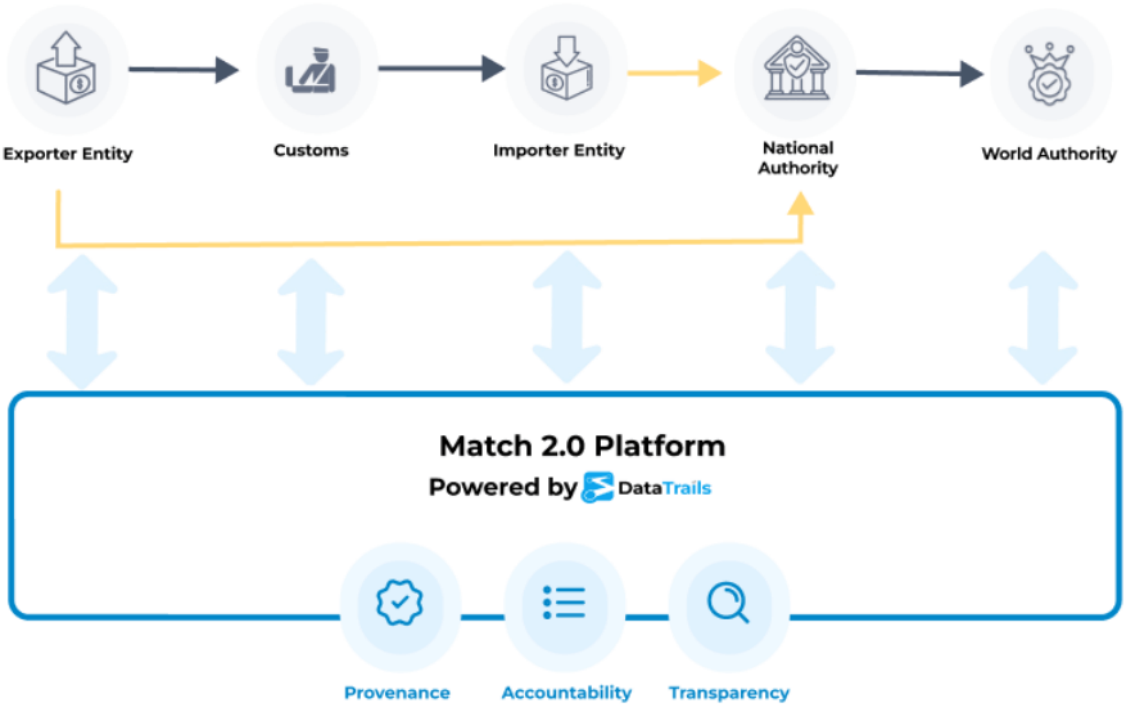
Unlike traditional blockchain systems that require complex consensus mechanisms and smart contracts, Forestrie focuses exclusively on the ledger layer—the mechanism that creates immutable audit trails—offering tamper-resistant auditability without the heavy computational cost. Forestrie uses Merkle trees which are essentially the coupling of hashes that are attached to each piece of data to create new fingerprints for those pairs, linking up the tree until one final fingerprint is left at the top, called the root hash. In Forestrie, every event gets its own entry as a 'leaf' of the tree and is individually, and independently verifiable and provable. Along with cybersecurity technologies, Forestrie makes it impossible to forge, back-date, or shred data. This solution creates detailed audit trails that allow for discrepancy identification and verification at the transaction level, resulting in a more scalable and accurate monitoring process for transfers of Schedule 2 and 3 chemicals.

Unlike fully centralized systems where administrators retain complete control (and potential liability), Forestrie creates multiple verification layers: data is first stored in secure databases, then committed to a verifiable ledger resistant to tampering even by DataTrails itself, then confirmed with signatures that resist Sybil attacks,[5] and finally distributed to prevent fork or substitution attacks by any party. This "defense in depth" approach means member states don't need to trust DataTrails or any single entity with the verification of their sensitive chemical trade data—the system's architecture provides mathematical verification without reliance on any central authority.

Forestrie also eliminates blockchain's well-known limitations. It doesn't require energy-intensive proof-of-work consensus mechanisms, operates without cryptocurrency incentives, and avoids complex smart contract programming that can introduce security vulnerabilities. The Merkle tree implementation used by Forestrie achieves

cryptographic verification with minimal computational resources—estimated to be orders of magnitude more energy-efficient than traditional blockchain approaches while maintaining the same immutability guarantees. These efficiency gains also translate to performance improvements: where blockchain networks might process tens of transactions per second with multi-minute confirmation times, Forestrie can handle hundreds of transactions per second with confirmation from the exporter to the NA and the World Authority within seconds as outlined in Figure 2.

Figure 2. MATCH 2.0 Powered by DataTrails



The MATCH team developed a series of use cases that mapped to a workflow expected in a real-world chemical trade operation. From that base, the team built in services to make MATCH intuitive and minimize friction associated with manual processes, automating as much as possible to create an experience that is clean and operator friendly. The result is a platform that, behind the scenes, delivers on the provenance, governance and immutability that Forestrie brings to bear for preventing errors at the front end while optimizing the reconciliation process at the back end.

Comparing the two prototypes, MATCH 2.0 user interface was more friendly and intuitive. True North took an end-to-end point of view when considering the development, the user interface, and user experience to reduce friction of implementing complex scenarios. This required a deep understanding of Forestrie and its workflow for

the distributed ledger and the workflows of all entities represented which could differ from region to region and NA to NA (such as with different reporting thresholds, decimal points and standardizing/automatically adjusting weights). The outcome was a more robust foundation that can be used to develop a production ready MATCH in the future.

By leveraging advancements in DLT, MATCH 2.0 provides a more promising solution for simplifying the reporting and reconciliation process while enhancing confidence in declared transfers thereby enabling States Parties to more effectively sift "through the noise" of the global chemical trade and focus on identifying activities that may indicate noncompliance or proliferation risks.

DEMONSTRATIONS, TESTING, AND FEEDBACK

Stimson's engagement with both Global Affairs Canada and the OPCW was critical for the success of MATCH. In 2021, the OPCW established the DLTRG (the DLT Reflection Group) with the mandate to engage with Stimson on MATCH. The DLTRG included representatives from the OPCW Verification Division, Information Services Branch, Office of Strategy and Policy, as well as from Canada's NA and Canada's Permanent Mission to the OPCW. Stimson's engagement with other NAs and the chemical industry globally was also critical to understanding the real-world potential of MATCH, particularly in testing MATCH and providing feedback for refinement. Both DataTrails and True North helped demonstrate MATCH to NAs and chemical industry and joined some meetings with the OPCW DLTRG to allow for comprehensive engagement with and response to stakeholders at all levels. As this was the first time that each company had engaged in the CWC and its implementation, these sessions also created learning within the tech industry as the project progressed.

The MATCH 2.0 team provided 19 demonstrations, 14 of which were to NAs. Also, a total of 12 NAs, 2 industry organizations, one civil society organization and the OPCW tested MATCH 2.0, logging 362 hours on the platform. In total 23 organizations were engaged.

During demonstrations, NAs raised a variety of issues, including data confidentiality and cybersecurity concerns, whether a deployed MATCH would achieve widespread adoption, how it handled differences in national legislation and whether MATCH would change current reporting procedures. There were also questions about costs and who would bear them. Among those that tested MATCH, feedback included the user interface and user experience (UI/UX) and how refinements could strengthen the platform. Testers also provided valuable feedback on how the role of customs could be better integrated into the platform.

Data and Cybersecurity

Data privacy, encryption, and security concerns could hamper adoption based on procurement and other requirements of each government and industry. Some countries may not want to replace existing secure systems they have invested in while others noted that if the system is promoted by OPCW, there may be fewer security-related barriers to adoption (such as with EDIS).[6] One NA mentioned that they would prefer data entry into MATCH to start at the NA level rather than at the industry level due to cybersecurity concerns.

Forestrie takes a multi-layered approach to security. Unlike traditional blockchain systems that require fully distributed deployment, Forestrie's architecture enables a hybrid model where sensitive data remains within an organization's security perimeter while still benefiting from distributed verification. The platform's "write-once" storage paradigm enhances security by eliminating modification vectors present in centralized databases. Each transaction is individually hashed and sealed into an append-only data structure, with previous entries becoming immutable upon commitment.

Forestrie also significantly mitigates data scraping concerns through its attribute-based access control model. Unlike blockchain's inherent transparency where all data is visible to all participants, Forestrie implements fine-grained permissions that limit data visibility only to authorized parties. Chemical trade data can be selectively shared, with exporters seeing only their outbound shipments and importers seeing only their inbound shipments. The system's cryptographic verification works without exposing the underlying trade details, allowing organizations to verify data consistency without revealing sensitive information.

Widespread Adoption

The OPCW's Verification Information System (VIS) developed by the Technical Secretariat manages all verification-related information to support verification activities.[7] In 2019, 53 NAs submitted their declarations in electronic format with 48 using the Electronic Declarations Tool for National Authorities (EDNA) for the preparation of Annual Declarations on Past Activities. In 2020, the Secretariat began the phaseout of EDNA and replaced it with the Electronic Declaration Information System (EDIS). By 2022, 24 NAs were using EDIS for submitting their annual declarations (the other 24 still used EDNA, and another 5 used their own electronic tools).[8] As of December 31, 2024, there were 39 NAs using EDIS for their 2023 declarations, 14 still using EDNA and six using their own software.[9]

EDIS is a distributed system (but not a distributed ledger) with multi-user access for both National Authorities and external users to streamline the collection of declaration information. Use of the system by States Parties is entirely voluntary. The EDIS software

runs on Windows operating system, on a stand-alone workstation or a Windows server.[10] The system is internally developed and maintained by the OPCW Secretariat and installed as software on a National Authority's computers. EDIS covers all declaration requirements for industry, including plant site declarations as well as aggregate annual totals of Schedule 2 and 3 chemicals traded. Data stored in NAs' local environments is exported into an XML file and transmitted to the OPCW via diplomatic means or the OPCW's Secure Information Exchange System (SIX).[11]

To adopt MATCH, some NAs said they may have to amend legislation to allow for third party software which would be a "huge challenge." However, many NAs stated that if MATCH was a portal offered by the OPCW, the challenge would be reduced, particularly for those that already use EDIS or EDNA. Integration and/or the interoperability of MATCH with EDIS is therefore key to its adoption at the OPCW level.

Since underreporting transfers within customs unions or free trade zones (FTZs) is one of the main causes of discrepancies, countries that are a part of such unions or zones are the most important to engage on tools to reduce or reconcile such discrepancies. Out of the 27 countries that make up the European Union, 15 currently use EDIS, representing more than half (55%) of the EU single market. If these 15 were to migrate to MATCH, for example, we anticipate a reduction of discrepancies that would incentivize other NAs to join over time. The experience of EDNA/EDIS by NAs to date indicates that adoption is slow given the time needed for review by national cybersecurity organizations. Similarly, the experience of EDIS also suggests that as more countries join over time and demonstrate its functionality and utility, more countries will follow, irrespective of industry size or chemical trade volume. The first six NAs to adopt EDIS, for example, all represented countries with relatively small chemical export and import volume.

There will always be countries that do not join a distributed system due to national policies (and will therefore always submit paper declarations, for example), but as more and more transfers are transacted among industry using DLT, identifying transfers involving non-MATCH countries will become easier during reconciliation. For example, if the fictional States Parties Gondwana and Laurentia from the MATCH ecosystem are both using MATCH and mandating its use by their chemical industry, transfers between chemical entities in each country will be reconciled at the transaction level, before submission to the NA. If, however, Baltica remains outside of MATCH, transfers between Baltica entities and Gondwana or Laurentia entities will not be reported to Baltica NA using MATCH, but they will still be reported to the OPCW via other means (whether its own electronic tool or by paper declaration). Gondwana and Laurentia would be using MATCH, however, which enables a quicker reconciliation process as transfer discrepancies will be flagged within MATCH.

Differences in National Reporting and Implementing Legislation

One of the significant attributes of DLT and of the MATCH platform is its ability to be tailored to each participant on the platform, and to each NA's different reporting threshold and frequency requirements. While many countries follow the concentration and quantity declaration thresholds defined in the CWC, for example, there are some NAs that have lower thresholds. MATCH can be tailored to log transactions exceeding any threshold defined by national implementing legislation.

One NA noted that national legislation in its country requires industry to report to the NA on each import and export when it occurs, not just annually when reporting aggregate volumes. MATCH can be tailored to the transaction-level, helping to resolve TDs before they occur at the entity level, as well as help in the reconciliation process for both industry and NAs. For countries where national legislation requires industry to report just once a year on aggregate quantities, MATCH would continue to allow industry to voluntarily log transactions and share transaction data with each other in near real time (reducing transaction level discrepancies), while ensuring NAs and the OPCW receive reporting only on an annual basis with aggregated data. Although some NAs voiced concerns about MATCH potentially enabling "verification creep," meaning visibility by NAs and/or the OPCW into industry's confidential transaction-level data not envisioned by the CWC nor by the national legislation of many countries, MATCH (and DLT) mirrors but does not change the CWC's reporting requirements nor national legislation.

Recognizing that the CWC and most national implementing legislation does not require reporting and declarations of individual transactions, some NAs and the OPCW identified a benefit if NAs were able to see the volumes and date of individual transfers. Others noted that NAs would benefit from seeing every transaction regardless of concentration thresholds. Tracking individual transactions would allow NAs to see the concentration level which may be lower than national or OPCW thresholds but go over the threshold when aggregated. Despite the "verification creep" concerns noted above and the reticence of some NAs to embark on the task of amending legislation, Stimson learned that a number of States Parties are in fact considering updates to their CWC implementing legislation and therefore may consider a transaction-based approach, particularly if MATCH is operable, as it would eliminate many TDs at the outset while making the reconciliation process easier at the back-end.

MATCH's tailorability and the wide variation in CWC implementing legislation and ecosystem in each State Party mean that developing a production platform for the real world would require a heavy lift in establishing the workflows for each individual country. Data flows across industry and government stakeholders in each country would need to be tailored and access policies baked into the platform as per national

legislation. For countries that designate customs authorities as the NA, the onboarding process will be more straightforward given their access to import/export permits. Countries that have clearly defined data flows and government and industry roles will also be more straightforward to onboard to the system. For others, the process of mapping of dataflows and compliance protocols will be more involved. At the same time, the more countries that are onboarded, the lower the overall onboarding time as the process becomes more streamlined – and therefore also more cost efficient.

The Costs

Given the differences in implementing legislation, Stimson and its developers anticipate varying costs based on the national legislation and the volume of industry transactions within a country. Some "larger" countries, or those with a robust chemical industry and large volumes of trade in scheduled chemicals, may also have more complicated national implementation and data flows, but this is not always the case. We can see examples, particularly when the NA and the customs authority are the same, where the costs will be more tied to the frequency of industry transactions rather than onboarding. Overall, costs involve the platform subscription (transaction based) and the onboarding process (which is more labor intensive). The more countries that are onboarded and the more the process becomes routine, the lower the overall onboarding costs.

Stimson continues to work with its developers to estimate the costs of a potential future follow-on project to bridge from MATCH's fictional platform to a real-world one by onboarding three to four NAs into a tabletop exercise. If the project moves forward, the exercise will yield additional insights, not only on the onboarding process and refinements needed to the UI/UX, but also on determining exact costs.

The User Experience

Stimson received comprehensive feedback on the user interface and the functionality of MATCH 2.0. Prompts and clarifications within the platform on decimal points, for example, could reinforce the OPCW standard of rounding to three decimal points and also alleviate regional differences in the use of commas versus decimal points. Drop-down menus for logging dates were suggested as well as prompts to remind industry that origin and destination refer to physical shipment locations, not financial transaction countries. It was also suggested that prompts be used to remind industry that transfers within customs unions and free trade zones must be logged as international transfers for CWC purposes.

Several NAs, when noting incorrect chemical names or CAS numbers as a cause of TDs, suggested that a column should be left open for entities to fill in with prompts of recommended Harmonized System (HS) codes, an international product nomenclature developed by the World Customs Organization (WCO) and used by governments,

international organizations, and the private sector for a range of purposes. However, other NAs expressed concerns about the lack of specificity in some HS chemical categories which can introduce ambiguity and additional reporting inconsistencies, and the WCO itself noted the challenges with accurately classifying chemicals under the HS and "a high demand for new classifications" for organic chemicals in its recent "Exploratory Study on a Possible Strategic Review of the HS – Final Report."[12] While CAS numbers can be difficult to track down, they are generally the preferred method given their specificity.

WHAT MATCH CANNOT DO

While MATCH can digitize and streamline reporting, eliminate some common clerical and other mechanical causes of transfer discrepancies, and provide forensic quality data, security, transparency, and permissioned confidentiality, it is important to note a few key things that DLT cannot, and MATCH would not be able to do.

One of the Stimson team's observations during MATCH 1.0 and MATCH 2.0 is the desire by many NAs and industry to go beyond reconciling TDs and use the platform to solve supply chain issues and support compliance with wider legislation. The EU Corporate Sustainability Due Diligence Directive, CSDDD, for example, entered into force in July 25, 2024, and requires companies to identify, prevent and mitigate human rights and environmental risks within their supply chains, for both direct and indirect suppliers. While DLT can certainly be a helpful tool in addressing these obligations they are specific to regional legislation and are outside of the scope of the CWC (and therefore of MATCH). That said, it is possible that industry could integrate MATCH with any system they adopt to address the EU CSDDD and other trade or supply chain-related legislation.

MATCH also cannot alter a country's CWC-implementing legislation or related laws and regulation. Amending national laws and standardizing global implementation is work that only States Parties can do. Nor can MATCH solve the pain of diplomatic routing through embassies, foreign ministries and other government agencies, if this is required by a State Party's protocol. While this decades-old system could benefit from updates, it involves many actors and remains beyond the scope of the CWC and MATCH.

One prominent critique during the project was that even if MATCH attracted 100 percent participation from all States Parties and their chemical industry, the whole system was simply "balancing the books for the sake of balancing the books." MATCH does not aim to detect deliberate smuggling or trafficking an illicit chemical shipment for nefarious purposes outside of the OPCW's accounting regime, but rather to enhance the efficiency and reliability of the existing accounting regime work to prevent and reconcile transfer discrepancies. Although the CWC does not explicitly require reconciliation of TDs, States Parties see the benefits of doing so as it not only provides a more accurate picture of their trade in scheduled chemicals but also makes it easier to

identify potentially bad actors and illegitimate trade. Until the global 'books' of good-faith actors can be balanced each year, ideally with significantly reduced time and labor requirements, both States Parties and the OPCW will remain uncertain about which shipments are genuinely problematic, and which are simply lost in the 'noise' of unresolved discrepancies, diverting time and resources that could be better spent addressing deliberate noncompliance.

CONCLUSION

In its first two decades, the CWC focused on the elimination of chemical weapons - leading to the destruction of over 40,000 metric tons of declared chemical weapons. With the destruction of the last declared chemical weapons stockpile in the United States in July 2023, the OPCW has entered a new phase focused on non-proliferation and preventing the reemergence of chemical weapons. Innovations in synthetic biology, artificial intelligence, big data analytics, and DLT have expanded both the threat landscape and the capabilities for enhanced information management and chemical weapons detection. International trade has therefore become "noisier" as technology not only advances but continues to converge (such as the convergence of AI, additive manufacturing and synthetic biology in the development of new chemical compounds and biological agents).

Many emerging technologies remain stalled in the so-called "innovation space," acknowledged for their promise but hindered by bureaucratic and structural inertia.[13] Over 3.5 years, MATCH has acted as an "incubator" for developing and testing DLT as a novel technology that has the potential to help alleviate the challenge of not only identifying but also resolving and reconciling TDs. A phased approach to testing and socializing DLT and the MATCH platform were key to the success of MATCH as it allowed space for NAs, industry, and the OPCW to share concerns, benefits, behavioral insights, and their understanding of institutional capabilities to cultivate an informed user base and close the gap between innovation and practical application. MATCH is thus well-positioned to transition from innovative concept to operational tool, supporting the CWC's continued relevance amid global technological transformation.

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[1] Data provided to the MATCH team by the OPCW on January 14, 2025.
[2] According to communication received from the OPCW on January 12, 2025.
[3] Percentages calculated from transfer discrepancy data reported in the OPCW's Annual Reports publicly available at https://www.opcw.org/resources/documents/annual-reports. The percentage for transfers conducted in 2023 was provided by the OPCW on January 14, 2025.
[4] https://www.stimson.org/2023/match-leveraging-blockchain-for-chemical-weapons-nonproliferation. See also: https://www.frontiersin.org/journals/blockchain/articles/10.3389/fbloc.2023.1151724/full.

[5] A Sybil attack is a type of cyberattack where an attacker creates multiple fake identities (Sybils) to gain disproportionate influence or control over a network or system, potentially disrupting its functionality or compromising its integrity.
[6] The Electronic Declaration Information System (EDIS) is a software application for National Authorities to create and submit the declarations required under Article III and Article VI of the Convention. "Electronic Declaration Information System," OPCW, 2025, accessed March 24, 2025, https://www.opcw.org/resources/declarations/electronic-declaration-information-system-edis.
[7] https://www.opcw.org/sites/default/files/documents/2020/01/ec93s03%28e%29.pdf.
[8] OPCW, 2022: www.opcw.org/sites/default/files/documents/2022/09/ec101s03%28e%29.pdf.
[9] Communication from the OPCW on April 4, 2025.
[10] OPCW, Electronic Declaration Information System (EDIS): https://www.opcw.org/resources/declarations/electronic-declaration-information-system-edis. Accessed March 23, 2025.
[11] Secretariat's Note S/1192/2014, dated 1 July 2014.
[12] WCO, "Exploratory Study on a Possible Strategic Review of the HS – Final Report," Brussels, October 2024, pp 29, 66. final-report-of-the-hs-exploratory-study-2024-english.pdf.
[13] Benjamin Kumpf and Parnika Jhunjhunwala, The Adoption of Innovation in International Development Organisations: Lessons for Development Co-operation, OECD Development Co-operation Working Paper 112, May 2023: www.ictworks.org/wp-content/uploads/2023/11/Adoption-of-Innovation-in-International-Development-Organisations.pdf.