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Asset tracking, condition visibility and sustainability using unmanned aerial systems in global logistics

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Abstract

The scale and scope of global logistics systems make real-time visibility of individual assets in global logistics systems difficult. Aggregating global logistics data to a manageable level where interruptions and disruptions can be anticipated or resolved is high on the wish list of global logistics managers and decision makers. Asset tracking and condition visibility in global supply chains is also difficult because few standards or metrics have been assessed in a supply chain, particularly when new technology is introduced, such as unmanned aerial systems in global supply chains. In this paper, we describe the integration of an unmanned aerial system in a global logistics system, and the metrics used to assess the integrated system. We highlight the importance of supply chain process, business impact, societal and environmental sustainability metrics, in addition to economic and supply chain performance metrics, in evaluating the integrated system.

1. Introduction

Global logistics systems connect critical elements of supply chains, impacting global and national economies as well as firms and multinational enterprises (Nicita et al., 2013; UNCTAD, 2019a). Delays in global logistics systems can stem from natural and environmental disasters, trade and tariff tensions, material and equipment unavailability, transportation and labor disruptions, disconnects between modes and transportation systems, and loss, damage and theft of material, equipment and systems (Fartaj et al., 2020; UNCTAD, 2019a). Global events, such as the COVID-19 virus outbreak, have also disrupted global logistics systems in ways and at scales not anticipated before (Anjumohan, 2020; McKibbin and Fernando, 2020; Ivanov, 2020). Impacts have included blank vessel sailings (Port Technology, 2020), passenger planes carrying air cargo in empty passenger aircraft seats (Chokshi, 2020), oil tankers circling offshore and ‘parked’ at sea (Low, 2020; Bousso and Saul, 2020) and shipped goods and equipment backed up for lack of storage and warehouse space (International Transport Forum, 2020). Global logistics systems delays and disruptions can be particularly acute in remote and infrastructure-poor settings, where access to material, personnel and equipment can be hampered by power and connectivity outages, food supply disruptions, weather and environmental conditions, as well as by political unrest (UNCTAD, 2019b; K&LGates, 2020; Reardon et al., 2020).

Visibility of delays in global logistics systems, and of the condition and quality of material, equipment and systems being carried in them, is central to effective and timely supply chain performance (Goel, 2010; Reyes et al., 2020). The scale and scope of global logistics systems make real-time visibility of individual assets difficult, and aggregating global logistics data to a manageable level where interruptions and disruptions can be anticipated or resolved is high on the wish list of global logistics managers and decision makers (Wieland et al., 2020). In remote and infrastructure-poor settings, real-time asset visibility can be a particular challenge, creating supply chain vulnerabilities. Addressing and assessing those vulnerabilities and challenges motivates this research.

Many technologies have been used to improve asset tracking and condition monitoring in global logistics systems, including radio frequency identification (RFID) systems, quick response (QR) codes and blockchain (Maritime Executive, 2020; Sarac et al., 2010; Reyes et al., 2020). Nanoscale sensors and systems, lightweight cameras and autonomous, unmanned aerial systems (UAS) have created opportunities to increase real-time asset visibility and condition reporting (Rong et al., 2020). In remote and infrastructure-poor settings, this visibility is of great importance as human observation and monitoring of assets can be difficult because of political, social or environmental issues (Verma and Lalwani, 2019).

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### Table 1
UAS - Supply chain impact metrics.

| Metrics | Description | Source |
|---------|-------------|--------|
| Supply chain performance metrics | • Supply chain reliability  
  • Supply chain responsiveness  
  • Supply chain agility  
  • Supply chain costs  
  • Asset management efficiency | Association for Supply Chain Management (ASCM), Supply Chain Operation Reference (SCOR) Model, 2020 |
| Material status metrics | Installation & construction metrics | Vrijhoef and Koskela, 2000; Bhatla et al., 2016; Omar and Nehdi, 2016; Wiengarten et al., 2016; Yun et al., 2016; Chen et al., 2017; Lee, 2017; General Electric, 2020 |
| Warehouse management metrics | • Asset exposed  
  • Items removed  
  • Changes in asset location  
  • Container condition  
  • Asset contents  
  • Deterioration over time | Ramaa et al., 2012 |
| Business impact metrics | Business productivity | Greger et al., 2018 |
| Sustainability metrics | Economic sustainability metrics | Kayikci, 2018 |

- Logistics costs  
- Delivery time  
- Transport delays  
- Inventory reduction  
- Loss/damage  
- Frequency of service  
- Forecast accuracy  
- Supply chain reliability  
- Supply chain flexibility  
- Supply chain transport volumes  
- Supply chain applications/Environmental sustainability metrics
Asset tracking and condition visibility is also difficult because few standards or metrics have been assessed in global logistics systems, particularly when new technology such as UAS is introduced (Biton et al., 2019; Reyes et al., 2020; Ghadge et al., 2020). This research addresses this gap and describes the integration of a UAS in a global logistics system, and the metrics used to assess the integrated system. The evaluation highlights the importance of supply chain process, business impact, societal and environmental sustainability metrics, in addition to economic and supply chain performance metrics, in evaluating the integrated system. The next sections describe previous work, including the use of UAS, in asset tracking and visibility, followed by a case study of a UAS integrated into a global logistics system. The metrics used to assess the integrated system are described, and gaps in the metrics, including sustainability metrics, are identified.

### 2. Asset tracking and visibility in global logistics systems

Real-time information in global logistics systems includes data such as asset and environmental temperature, humidity, moisture levels, location, magnetic fields, and vibration and shock metrics (Zhang et al., 2018a; Teucke et al., 2018; Cai et al., 2014). Physical and virtual checkpoints in supply chains and Internet of Things (IoT) sensors can speed information flow, providing real-time shipment visibility even when the shipment is not in transit (Teucke et al., 2018; Reyes et al., 2020; Shah et al., 2020; Vamsi et al., 2020; Zhang et al., 2018a; Ben-Daya et al., 2019).

Despite these advances, global supply chains still face challenges in obtaining and securing real-time inventory updates (Bányai, 2018) and product quality and control data (Mejiaouli and Babiceanu, 2018), especially in large-scale infrastructure and development projects, where material and equipment can arrive at installation and construction sites well in advance of their use or installation (Piskuric, 2017). Real-time information in global supply chains can be interrupted by sensor incompatibilities with integrated supply chains, disconnects between data and reporting taxonomies and standards (Zhang et al., 2018b; Mejiaouli and Babiceanu, 2018), missing or unavailable transportation checkpoints, and signal drops, power and connectivity issues (Giusti et al., 2018; Teucke et al., 2018; Zhang et al., 2018b; Torabbeigi et al., 2019). Although infrared communications, micro radio links, Global Positioning Systems (GPS) and other real-time locational technologies can provide important data, the absence of signals or connectivity still poses difficulties (Cheng et al., 2011; Giusti et al., 2018; Teucke et al., 2018).

UAS have been introduced in global logistics systems to address some of these challenges, supporting warehouse, freight and logistics operations (Baniasadi et al., 2020; Vamsi et al., 2020; Fournami et al., 2018; Zhang et al., 2018b), providing real-time information on material and equipment condition and quality (Azmat and Kummer, 2020). UAS have been deployed in Wal-Mart warehouses, and have cut inventory time from thirty days to just one, with costs, compared to a human employee, cut approximately in half (Companik et al., 2018). Amazon's UAS have been able to reduce shipping times, with UAS-supported warehouses able to carry 50% more products, with 20% lower operating costs (Companik et al., 2018) and last-mile delivery costs estimated to be similarly reduced (Aurambout et al., 2019). 5G wireless Internet is expected to provide significantly improved UAS performance compared to fourth generation (4G) technology, improving information reliability and latency (Brake, 2020; Huo et al., 2018; Rao and Prasad, 2018).

UAS have used image processing and deep learning algorithms to achieve collision-free flight (Schilling et al., 2018), and autonomous UAS can be programmed to return to their charging areas when their batteries are low (Hassija et al., 2020; Zhang et al., 2018b). UAS swarms or ‘flocks’ can deploy force-multiplying capabilities and use multi-agent architectures to share power and resources, in an effort to dampen communication and power vulnerabilities (Alladi et al., 2020), improving locational and target accuracy (Schilling et al., 2018). External aids, such as markers or sensors, can guide UAS travel, improving autonomous navigation, supporting UAS tracking beyond settings where the UAS must follow a prescribed route (Papakonstantinou et al., 2019). In some instances, autonomous UAS have persisted even when they experienced loss of visual tracking and communication delays (Torabbeigi et al., 2019; Papakonstantinou et al., 2019).

To address power, connectivity and communication issues, UAS have been linked to terrestrial delivery vehicles, which can serve as power sources and replenishment sites, making other deliveries before the UAS returns to the vehicle (Chiang et al., 2019). As such, UAS can serve as last mile delivery vehicles in remote areas (Aurambout et al., 2019; Chiang et al., 2019), particularly in humanitarian (Azmat and Kummer, 2020), disaster response and recovery (Ejaz et al., 2020) and medical settings (Zubin et al., 2020). UAS can also offer a number of sustainability advantages, reducing or transferring transportation costs to ‘greener’ modes (Azmat and Kummer, 2020), and perhaps reducing the 15% of global carbon dioxide (CO2) emissions attributed to the transportation sector (Rodrigue, 2019; Kamble et al., 2020). UAS themselves can also incorporate sustainable power sources, materials and payloads, presenting a smaller carbon footprint.

### 3. UAS impact and asset tracking

Many candidate metrics and conceptual frameworks have been proposed to assess supply chain performance (Ramaa et al., 2012; Dunke et al., 2018) (Table 1); in this research we consider those metrics in light of new technology being introduced into global supply chains, notably UAS.

| Table 1 (continued) |
|---------------------|
| **Metrics** | **Description** | **Source** |
| Resource efficiency | | |
| Process energy | | |
| Process emissions | | |
| Waste | | |
| Pollution | | |
| Land use impact | | |
| Societal sustainability metrics | | |
| Development impacts | | |
| Societal impacts | | |
| Health impacts | | |
| Safety impacts | | |
| Labor impacts | | |
| Societal acceptance | | |

Many supply chain performance metrics have been proposed, including those published by the Association for Supply Chain Management’s Supply Chain Operation Reference (SCOR) model (Association for Supply Chain Management (ASCM), 2020) (Table 2 in Appendix A). Applying these metrics to new technology introduction in global supply chains links the presence, absence or performance of new technology to supply chain reliability, efficiency, responsiveness, agility and cost. Material status and business impact metrics can be used to assess the impact of new technology introduction efforts on equipment and material status as well as financial...
and other business impacts (Tables 3 and 5 in Appendix A) (Vrijhoef and Koskela, 2000; Bhatla et al., 2016; Omar and Nehdi, 2016; Wiengarten et al., 2016; Yun et al., 2016; Chen et al., 2017; Lee, 2017; Greger et al., 2018; General Electric, 2020). Warehouse management metrics (Table 4 in Appendix A) (Ramaa et al., 2012); and supply chain sustainability metrics (Table 6 in Appendix A) (Kayikci, 2018) can provide insight as to in-
transit and storage location impacts of new technology introduction, as well as input to understanding the long-term viability of technology in global supply chains. Definitions and cross references for these sources are presented in Appendix A. Fig. 1 shows that supply chain impact metrics focus on the supply chain or system level (Tables 2, 5 and 6), the warehouse level (Table 4), and the asset or material level (Table 3). The case study that follows considers these metrics in the context of a prototype technology integration project linking a UAS and a global logistics system, and highlights where future work is needed.

4. Case study: UAS in a global logistics systems

Nearly 1 billion people lack access to reliable power, motivating growing demand for cost-effective, reliable and energy-efficient power (Fig. 2; GE Power, 2020a, 2020b). Global power generation capacity is expected to top 12TW by 2050, requiring $13.3 trillion of new investment in power plants (Bloomberg New Energy Futures, 2019). Building this energy capacity requires new power plants, which cost, on average, hundreds of millions of dollars (U.S. Energy Information Administration, 2018).

Building power plants entails shipping thousands of cases of parts, equipment and subsystems through global supply chains that connect manufacturers and suppliers with plant sites. Cases can range in value from small ($15) units of washers or plugs to significant ($20M) system components such as turbines, pumps and generators, which can represent 10–20% of a power plant’s installation and construction costs (GE Power, 2020c). New plant sites are often in remote and infrastructure-poor settings, consistent with power needs, but complicating shipping and logistics.

Delays in shipping parts and equipment can run up to $25M daily for a gas power plant (GE Power, 2020c), and delays in shipping can account for 5–15% of the total cost of a construction project, so global logistics systems that reduce even a day’s delay in shipping parts, equipment and systems can have significant impact on total project cost (A&A, 2020). In this case study, UAS were linked to a global logistics system for a multinational power systems vendor in order to provide real-time ‘eyes on’ visibility of asset status and condition in the power plant construction area (the demonstration ‘laydown yard’). An analysis of the prototype system identified metric and data gaps and suggested the need for new metrics.

4.1. Background

The setting for the case study is a remote, infrastructure-poor environment similar to those of a new power plant installation and construction project (Fig. 3). The laydown yard houses assets and equipment to be installed in the power plant for up to several years, making asset tracking, condition monitoring and reporting challenging. In the prototype demonstration, a UAS was linked to land-based beacons in a prototype laydown yard. The UAS technology was a fixed wing SkyHunter 1800 mm FPV/UAV (Fig. 4) outfitted with sensor packages (Fig. 5), a Bluetooth reader (Fig. 6), and a communication device to link the UAS and the ground station. The sensors on the ground-based assets provided data such as temperature, pressure, and humidity. When paired with the UAS sensors that provided GPS coordinates, asset location, movement, tracking and position could be determined.

4.2. Data collection

The notional data collection process is illustrated in Fig. 7. Upon arrival at the laydown yard, assets could be registered and logged by asset sensors;
4.3. Method

To demonstrate the viability of the integrated system, sample data from UAS overflights of asset beacons in the prototype system were gathered over a 3-month period between November 2019 and February 2020. Data gathered included latitude and longitude of the UAS sensors and of the asset beacons, and of the flight path over time. Environmental data, including temperature, humidity, wind and barometric pressure, all of which can impact sensor performance, asset condition, and camera performance, were also captured during the overflight. The overflight data were assessed for integrity, accuracy and reliability by an FAA Part 107-certified UAS pilot and the data compared with attributes in the WMSA application. The Table 1 metrics were mapped to the WMSA and UAS integrated system, as seen in Table 7.

4.4. Analysis

The Table 1 metrics were compared to those that could be captured in the UAS-logistics system demonstration. Some of this data was captured using UAS-based sensors, such as ‘Physical Location’ and ‘Material Location’. Other data was collected manually. Table 7 shows which metrics could and could not be collected using UAS-based sensors: some supply chain cost, installation part requests, packing list discrepancies and quality information could be captured by the integrated UAS –
Table 7
Prototype demonstration metric mapping.

| Metrics                                | Description                          | Metrics mapped | Metrics not mapped                           |
|----------------------------------------|---------------------------------------|----------------|----------------------------------------------|
| Supply chain performance metrics       | Supply chain costs                    | A1, A2, A3, E1, E2 | Supply chain reliability                      |
| Table 2                                |                                       |                | Supply chain responsiveness                   |
|                                        |                                       |                | Supply chain agility                          |
|                                        |                                       |                | Asset management efficiency                   |
|                                        |                                       |                | Over shortage, damage claims                  |
|                                        |                                       |                | User access, repeat users                     |
|                                        |                                       |                | Process performance                           |
|                                        |                                       |                | Management performance                        |
|                                        |                                       |                | Waste, asset location                         |
|                                        |                                       |                | CooperationSupply chain metrics               |
| Material status metrics                | Installation & construction metrics    | D5             | Supply chain efficiency                       |
| Table 3                                | Installation part requests             |                | Supply chain effectiveness                    |
|                                        | Number of part reorders at site       | A4             | Supply chain inventory                         |
|                                        | Packing list discrepancies            | B1             | Supply chain operational dates                 |
|                                        | Quality of service                    | B4             | Supply chain shortages                         |
|                                        | Real time logistics metrics           | B3, B5, B6     | Defective, misused materials                   |
|                                        | Real time visibility                  |                | System architecture                           |
|                                        | Supply chain metrics                  |                | • System architecture alignment                |
|                                        | Poor quality materials                | A3, B2         | • Completeness                                |
|                                        |                                       |                | • Deterioration over time                     |
| Warehouse management metrics           | Asset exposed                         | C1, C5         | Invoice preparation time                      |
| Table 4                                | Items removed                         | C4             | Order entry time, close effort                 |
|                                        | Changes in asset location             | B6, C2         | Financial impact                              |
|                                        | Container condition                   | D1             | • Outage delaysProcess compliance             |
|                                        | Asset contents                        | B2, C3         | • Closeout delaysController compliance        |
| Business impact metrics                | Business productivity                 | D5             | • Close cycle time                             |
| Table 5                                | Storage inventory                     |                | Process performance                           |
|                                        | Work package assembly time            | D4             | Economic sustainability metrics                |
|                                        | Financial impact                      |                | • Delivery time, transport delays             |
|                                        | Lift costs                            | D2             | • Inventory reduction                         |
|                                        | Controller compliance                 |                | • Loss/damage                                 |
|                                        | Condition assessment                  | C5             | • Frequency of service                         |
|                                        | Customer fulfillment                  |                | • Forecast accuracy                            |
|                                        | Storage footprint                     | D3             | • Societal sustainability metrics              |
| Sustainability metrics                | Economic sustainability metrics       |                | • Development impacts                         |
| Table 6                                | Logistics costs                       | E1             | • Societal & labor impacts                    |
|                                        | Loss/damage                           | E2             | • Health & safety impacts                     |
|                                        |                                       |                | • Societal acceptance                         |
|                                        |                                       |                | • Connectivity acceptable                     |

Technology metrics (new) Technology connectivity

logistics system. At the same time, Table 7 highlights the gaps in metric capture in supply chain efficiency, business productivity and sustainability metrics. Although the prototype mapping results may reflect that UAS data capture was focused on tracking the presence, location and condition of assets in warehouses, the large gaps in supply chain, business impact and sustainability metrics that could be captured with an integrated UAS logistics system are notable and indicative of where future research could be focused. Table 7 also highlights the growing need for new logistics connectivity metrics, particularly as global logistics systems managers, decision makers and regulators will increasingly rely on the availability of the real-time data.

Table 7 highlights where additional research and data capture is needed, notably in environmental and societal sustainability metrics; in new technology adequacy metrics; and in supply chain efficiency, effectiveness, reliability and responsiveness metrics. Table 8 in the Appendix further delineates the data elements, data sources and data types for the available and new metrics.

5. Conclusion

The case study demonstration highlighted gaps in global logistics metrics that could be captured by integrating UAS-captured data (Table 7) and new data fields and metrics that could support asset tracking and condition monitoring (Table 8 in the Appendix). These results are particularly of interest in infrastructure-poor settings where human observation of individual assets may be difficult, as may be the case in international infrastructure development projects. In projects such as power plant installations or bridge or port
developments, UAS could be used to gather and monitor data about components or systems that can arrive a year or two before they are installed at the development site. Tracking these components or systems and their location and condition is important, as human eyes-on data gathering might be difficult over time, or because of social or political reasons. The results in Table 7 also underscore the need to include environmental and societal sustainability metrics, in addition to economic impact metrics.

Different metrics were expected to provide measures of different facets of global logistics systems. Supply chain performance metrics described expected supply chain benefits, including cost reductions, and verification that the correct assets were shipped to correct locations within a given quality threshold. Cost reduction data considered both pre-implementation and post-implementation direct and indirect costs. Determining whether assets arrived with the correct asset quantity and quality is critical and in this demonstration could be captured using UAS data capture.

Material status metrics centered on tracking and reporting on individual assets, which could be tracked upon first arrival at the laydown yard, using ground-based beacons. The UAS sensors could determine the beacon location, ambient humidity, and asset vibration, as input to determining asset condition. The case location could be cross referenced to the asset location, and any discrepancies noted. A case beacon could report to the UAS any case vibration that occurred, as well as reported humidity levels; this information could then be used to determine whether case contents exceeded their thresholds. In addition to asset information, sensor quality and condition could also be reported in each UAS scan, providing data to quality of sensor service metrics. Material status metrics could also be used to track asset quality over time. Cases that are examined during initial inspection could have their packing lists validated and the number of items within a case that do not meet standards could be identified. These metrics give logistics decision-makers insight into asset inventory, trends and patterns, as well as into the strength of the data capture and analysis system. Regulators may also have interests in the real-time status or perhaps deterioration of safety-critical items or systems, or in trends that are precursors to the onset of adverse events.

Warehouse management metrics assessed asset maintenance and security conditions. Cases stored in laydown yards can become exposed to the elements, which could be detected by a solar strength indicator or a humidity sensor; this information could provide indications of whether an asset was exposed, and whether action to redress the exposure was required. Items in each case could be verified against packing lists, and removed items could be flagged or tracked if reorders were needed. Each case and its items could also project a location to the UAS sensors, which could be monitored to determine whether an asset was stolen, moved, or used. Taken collectively, these metrics can inform decision makers about the status of each case and its contents, and provide aggregate and individual asset visibility data and trends, a capability of high interest to logistics systems managers, decision makers and, in the case of sensitive or hazardous cargo, regulators.

Business impact metrics overlapped with the Supply Chain Performance Metrics, and included case and item condition assessment data, including humidity and vibration sensors. Calculations of the time to locate parts, along with the number of tracked parts, could provide insight as to whether a tracked case incurred damage, was moved, or was detected with a failing beacon. Business impact metrics focused not only on supply chain performance, but also on the financial and logistical effects on supply chains. Data showing the time to get a required asset on site, its order date and delivery date, combined with asset and warehouse and storage capacity limits, provide real-time visibility of asset readiness and asset-based impacts on project cost and performance. These metrics are difficult to obtain manually, especially in remote and infrastructure-poor settings, and the real-time visibility and status information provided by the integrated UAS-logistics system could provide key input to project planning and cost monitoring decision-makers. Lift cost, for instance, is important when items need to be provided quickly and reliably. Delays or life cost reductions can provide key input to decision makers considering the overall viability of a project or plant.

Sustainability metrics are critical for logistics system and power plant success, and included metrics for logistics costs, loss or damage, safety events and project acceptance. Pre- and post-implementation data could provide a baseline against which future data and trends can be benchmarked. In this work, demonstration data on the overall costs of logistics, including warehousing costs, could provide indicators of a project’s costs and benefits. The total costs of lost or damaged items, along with the number of reported safety incidents, could be captured in the integrated UAS-logistics system. More difficult to capture, and missing from this demonstration, were environmental and societal sustainability metrics or data, which could provide indicators of the short- and long-term viability of projects and power plants. This work highlighted their absence from the technology demonstration and underscored the importance of their inclusion in future work. Capturing and calculating resource and process efficiency; waste, pollution and land use impact; and development impacts could be automated and perhaps improved with an integrated UAS-logistics system that captured input metrics through ground- and UAS-based sensors. More difficult, and perhaps more important to project and logistics system viability, however, are determining the societal, health, safety, labor and social acceptance impacts of large-scale development projects supported by global logistics systems; this is particularly the case in remote and infrastructure-poor settings, which suggests fruitful areas for future work.

Integration of a UAS into a global logistics system can provide logistics decision makers visibility of and access to real-time data that can be difficult to obtain and of great economic value. At the same time, the regulatory and policy implications of integrating UAS and real-time logistics data are significant and evolving. UAS-based cameras and sensors can generate large volumes of unstructured (image, video, animation, sound) data. Integrating large unstructured data sets with existing structured (text, numeric) data in legacy logistics systems can present data validation, migration and integration challenges. Regional, national and international standards for these data types are under development, but the integration and interoperability standards and metrics for seamless global logistics systems utilizing large repositories of structured and unstructured data are lagging technology deployment. Regulatory and governance issues around data ownership, data sharing and privacy will also continue to present challenges in the years to come.

CRediT authorship contribution statement

Ethan Sellevold: Conceptualization, Formal analysis, Writing-original draft. Travis May: Conceptualization, Formal analysis, Writing-original draft. Sam Gangi: Conceptualization, Formal analysis, Writing-original draft. Jakub Kulakowski: Conceptualization, Formal analysis, Writing-original draft. Ian McDonnell: Supervision, Validation. Doug Hill: Supervision, Validation. Martha Grabowski: Funding acquisition, Supervision, Validation, Visualization, Writing-review & editing.

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Table 2

Supply chain impact metrics Association for Supply Chain Management (ASCM), Supply Chain Operation Reference (SCOR) Model (2020).

| Reliability | Responsiveness | Agility | Cost | Asset Management Efficiency |
|-------------|----------------|---------|------|-----------------------------|
| RL.1.1: Perfect Order Fulfillment | RS.11.1: Order Fulfillment Cycle Time | AG.11.1: Upside Supply Chain Adaptability | CO.1.1: Total Supply Chain Management Costs | AM.1.13: Cash-to-Cash Cycle Time |
| RL.3.3.1: Delivery Item Accuracy | RS.3.8: Authorize Supplier Payment Cycle Time | AG.12.2: Upside Adaptability (Supplier) | CO.1.2: Cost to Plan Supply Chain | AM.1.31: Days Gross Outstanding |
| RL.3.3.5: Delivery Quantity Accuracy | RS.3.35: Identify Sources of Supply Cycle Time | AG.12.3: Upside Adaptability (Delivery) | CO.1.3: Cost to Plan (Source) | AM.1.2: Inventory Days of Supply |
| RL.2.7: Delivery Performance to Customer Commit Date | RS.3.3.7: Receive Product Cycle Time | AG.12.4: Upside Return Adaptability (Source) | CO.1.4: Cost to Plan (Make) | AM.1.3: Inventory Days of Supply (Raw Material) |
| RL.3.3.2: Customer Commit Date Achievement Time | RS.3.12: Schedule Product Deliveries Cycle Time | AG.12.5: Upside Return Adaptability (Delivery) | CO.1.5: Cost to Plan (Delivery) | AM.1.3.7: Inventory Days of Supply (WIP) |
| RL.3.3.4: Delivery Location Accuracy | RS.3.3.9: Select Supplier and Negotiate Cycle Time | AG.12.6: Downside Supply Chain Adaptability | CO.1.5.5: Cost to Plan (Return) | AM.1.3.12: Inventory Days of Supply (Finished Goods) |
| RL.3.3.3: Documentation Accuracy | RS.3.19: Transfer Product Cycle Time | AG.12.7: Downside Adaptability (Delivery) | CO.2.2: Cost to Source | AM.1.3.14: Inventory Days of Supply (Finished Goods) |
| RL.3.3.1: Compliance Documentation Accuracy | RS.3.40: Verify Product Cycle Time | AG.12.8: Downside Adaptability (Make) | CO.2.6: Cost to Source | AM.1.2: Return on Supply Chain (Net Return) |
| RL.3.4: Return Orientation | RS.2.2: Make Cycle Time | AG.12.1: Overall Value at Risk (VAR) | CO.2.9: Cost to Transfer Product | AM.2.4: Supply Chain Revenue |
| RS.3.4: Return Orientation | RS.3.36: Finalize Production Engineering Cycle Time | AG.12.2: Supplier/Customer/ Product’s Risk Rating | CO.3.0: Cost to Verify Product | AM.2.5: Supply Chain Fixed Assets |
| RL.3.5: Payment Documentation Accuracy | RS.3.48: Issue Material Cycle Time | AG.12.3: Value at Risk (Plan) | CO.3.2: Cost to Make | AM.3.1.1: Fixed Asset Value (Delivery) |
| RL.3.5.1: Shipping Documentation Accuracy | RS.3.50: Produce and Test Cycle Time | AG.12.4: Value at Risk (Source) | CO.3.3: Direct Material Cost | AM.3.1.8: Fixed Asset Value (Make) |
| RL.3.6: Order Processing | RS.3.31: Release Finished Product to Deliver Cycle Time | AG.12.5: Value at Risk (Make) | CO.3.10: Indirect Cost Related to Production | AM.3.3.1: Fixed Asset Value (Plan) |
| RL.3.6.3: Order Processing | RS.3.32: Schedule Production Activities Cycle Time | AG.12.6: Value at Risk (Delivery) | CO.3.11: Direct Labor Cost | AM.3.3.2: Fixed Asset Value (Return) |
| RL.3.7: Order Processing | RS.3.35: Stage Finished Product Cycle Time | AG.12.7: Value at Risk (Return) | CO.2.4: Cost to Deliver | AM.3.7.7: Fixed Asset Value (Source) |
| RL.3.8: Order Processing | RS.3.38: Package Cycle Time | AG.12.8: Value at Risk (Total) | CO.3.34: Order Management Costs | AM.1.13: Return on Working Capital |
| RL.3.9: Order Processing | RS.2.3: Deliver Cycle Time | AG.12.9: Overhead Cost | CO.3.35: Order Delivery and / or Install Costs | AM.2.6: Accounts Payable (Payables Outstanding) |
| RL.3.9.1: Reduced Order Processing | RS.3.16: Build Loads Cycle Time | AG.12.10: Indirect Cost | CO.2.6: Cost to Source | AM.2.7: Accounts Receivable (Debts Outstanding) |
| RL.3.9.2: Reduced Order Processing | RS.3.18: Consolidate Orders Cycle Time | AG.12.11: Indirect Cost | CO.3.12: Cost to Source Return | AM.2.8: Inventory |
| RL.3.9.3: Reduced Order Processing | RS.3.41: Install Product Cycle Time | AG.12.12: Indirect Cost | CO.3.13: Cost to Deliver Return | |
### Table 3
Material status metrics.

| Metric                              | Measurement                                      | Source/reference |
|-------------------------------------|--------------------------------------------------|------------------|
| Installation part requests          | Number of part requests ordered weekly/monthly   | GE, 2020         |
| Number of part reorders at site     | Number of parts reordered at the site weekly/month | GE, 2020         |
| Over shortage and damage claims     | Cost of extra or damaged parts arriving at construction site per week/month | GE, 2020         |
| Packing list discrepancies         | Number of packing list discrepancies per week/month | GE, 2020         |
| User access/repeat users            | Number of users/Repeat users weekly              | GE, 2020         |
| Quality of service                 | Expected vs. experienced service                 | Lee, 2017        |
| Process performance                | Process performance: accuracy, cost, security and timeliness. | Yun et al., 2016 |
| Management performance indicators  | Management performance vs. identified goals      | Chen et al., 2017 |
| Waste reduction                    | Waste reduced because of total site organization | Vrijhoef and Koskela, 2000 |
| Cooperation                        | Degree to which system components work together. | Vrijhoef and Koskela, 2000 |
| Material location                  | Amount of materials with accurate system locations | Omar and Nehdi, 2016 |
| Real-time visibility               | Degree to which decision makers have visibility of asset location, condition, status | Omar and Nehdi, 2016 |
| Efficiency                         | Supply chain efficiency                          | Wiengarten et al., 2016 |
| Effectiveness                      | Supply chain effectiveness                       | Wiengarten et al., 2016 |
| Inventory                          | Number of parts recorded in inventory            | Wiengarten et al., 2016 |
| Operational dates                  | Number of days aligned with operational dates    | Wiengarten et al., 2016 |
| Shortages                          | Amount of material shortages                     | Bhatla et al., 2016 |
| Defective materials                | Amount of materials that arrive that are defective | Bhatla et al., 2016 |
| Misuse                             | Amount of materials damaged due to misuse        | Bhatla et al., 2016 |
| Poor quality                       | Amount of materials that don't meet requirements due to quality | Bhatla et al., 2016 |
| Alignment                          | How accurately the architecture reflects design requirements | GE, 2020         |
| Completeness                       | How complete the architecture is, compared to decision making needs | GE, 2020         |

### Table 4
Warehouse management metrics (Ramaa et al., 2012).

| Metric                              | Definition                                      |
|-------------------------------------|--------------------------------------------------|
| Asset exposed                       | Whether the asset has been exposed to the environment outside its container. |
| Items removed                       | Whether and how the asset has had items removed from its packaging or container. |
| Changes in asset location           | Whether and how the asset's location has changed |
| Containment condition               | The condition of the asset's container           |
| Asset contents                      | The presence and/or condition of the asset's contents |
| Deterioration over time             | Whether and if the asset has deteriorated over time. |

### Table 5
Business impact metrics (Greger et al., 2018).

| KPI/metric name · (Category)        | Definition                                                                 |
|-------------------------------------|----------------------------------------------------------------------------|
| Invoice preparation time (productivity) | The time required for a CPM to define the list of items to be included on a monthly or quarterly invoice, including fixed and variable fees, and calculate price for each line. |
| Order entry time (productivity)     | The time required performing all order entry steps that occur between the approval of an ITO/OTR Handoff meeting and the closure of the Opportunity, indicating the Operations team may begin work on the contract. |
| Post outage delay (business financial) | Time between demobilization from the customer site and final cost accumulation to the contract for the outage. |
| Closeout delay (process compliance) | Time between the last cost accumulation or customer invoicing event on a contract and the closure of the contract in ERP. |
| Close effort (productivity)         | Manual effort applied to the entire closing process                         |
| Close cycle time (controller compliance) | Time from start of closing process to availability of period financials. Start at closing of first module and End when all modules are open for transactions for the following period. |
| Storage footprint (customer fulfillment) | Space required for storage.                                                  |
| Storage inventory (productivity)    | Time required to search for and locate parts                                 |
| Lift cost (productivity)            | Cost of locating and building activity plans (Lift cost)                     |
| Work package assembly time (productivity) | The amount of time it takes to identify all components to be installed and collect them at site in time for installation |
| Condition assessment (controllership compliance) | The % of failed scheduled inspections per case; connect humidity indicators to RFID to determine how many cases have exceeded humidity % |

### Table 6
Sustainability metrics (Kayikci, 2018).

| Sustainability dimensions | Sustainability criteria | Description                                                                 |
|---------------------------|-------------------------|-----------------------------------------------------------------------------|
| Economy                   | Logistics cost          | Changes in logistics cost savings in terms of transport, warehousing, inventory carrying and administration costs |
|                           | Delivery time           | Changes in delivery improvements, cycle time, lead time                      |
|                           | Transport delay         | Changes in the amount of delayed shipment                                    |
|                           | Inventory reduction     | Changes in inventory volume                                                  |
|                           | Loss/damage             | Changes in the amount of lost and/or damaged goods from damage, theft and accidents |
|                           | Frequency of service    | Changes in utilization rate (load factor), frequent intervals                 |
|                           | Forecast accuracy       | Changes in demand uncertainties                                              |
|                           | Reliability             | Changes in logistics quality in terms of transport, inventory and warehousing e.g. perfect order, scheduled time deliveries |
### Table 6 (continued)

| Sustainability dimensions | Sustainability criteria | Description |
|---------------------------|-------------------------|-------------|
| Environment               | Flexibility             | Changes in planning conditions e.g. percentage of non-programmed shipments executed without undue delay |
|                          | Transport volumes       | Changes in total transported freight volume |
|                          | Applications            | Suitable applications for digitization in logistics processes |
|                          | Resource efficiency     | Non-renewable resources consumption in use of vehicles and transport facilities |
|                          | Process energy          | Changes in energy requirements |
|                          | Process emissions       | Changes in fuel consumption, CO₂ and other greenhouse emissions |
|                          | Waste                   | Changes in the amount of recyclable waste |
|                          | Pollutions              | Changes in air, noise and water pollution |
|                          | Land use impact         | Changes in land area devoted to transport facilities and rates of land loss |
| Society                  | Development benefits    | Open source appropriate technology implications for self-directed sustainable development |
|                          | Social impacts          | Social impacts generated through digitization in logistics |
|                          | Health impacts          | Changes in disease caused by transport side effects (pollution, noise...) |
|                          | Safety impacts          | Changes in the amount of accident related disabilities and fatalities |
|                          | Labor pattern impacts   | Changes in labor intensity, employment schemes, and types of work |
|                          | Social acceptance       | Socio-economic, community and market acceptance of digital applications |

### Table 8

**Case study UAS – WMSA metric analysis.**

| Source | Metric | Data element | Data source | Data type |
|--------|--------|--------------|-------------|-----------|
| A. Supply chain performance metrics | Metric A1 = Direct material cost | WMSA: 'Cost per UAS and associated systems', 'sensor cost', 'number of tracked shipments', 'wages paid', 'cost cut' | New metric proposed - WMSA | Calculated |
|       | Metric A2 = Indirect costs | WMSA: 'Cost of adopting system', 'project adoption costs', 'unforeseen expenses' | New metric proposed - WMSA | Calculated: |
|       | Metric A3 = Correct quality | WMSA: 'Correct quality', 'incorrect quality' | New metric proposed - WMSA | Binary: 'Correct quality', 'incorrect quality' |
|       | Metric A4 = Correct quantity | WMSA: 'Correct quantity', 'incorrect quantity' | Origin – ASCM 2019 | Binary: 'Correct quantity', 'incorrect quantity' |
| B. Material status metrics | Metric B1 = Packing list discrepancies | WMSA: 'Correct packing list', 'incorrect packing list' | GE WMSA data set | Binary: 'Correct packing list', 'incorrect packing list' |
|       | Metric B2 = Poor quality | WMSA: 'QUALITY STANDARDS', 'ASSET CONTENTS', 'CASE' | GE WMSA data set | Binary: Poor/acceptable quality |
|       | Metric B3 = Asset location | WMSA: 'Tracked assets' | GE WMSA data set | Calculated: Asset location |
|       | Metric B4 = Quality of service | WMSA: 'Expected service', 'service provided' | GE WMSA data set | Binary: Quality of service = Expected/not as expected |
|       | Metric B5 = Asset location by date/time | UAS Data: 'Latitude,', 'longitude;', 'date/time' | 11/11/2019 UAS | Alphanumeric: Latitude, longitude |
|       | Metric B6 = Physical Inventory location | UAS Data: 'Last reported location', 'provided location' | GE WMSA data set | Calculated: PIA = [Last reported location vs. provided location] |
| C. Warehouse management metrics | Metric C1 = Asset exposed | UAS Data: 'Exposed', 'not exposed' | GE WMSA data set | Binary: 'Exposed', 'not exposed' |
|       | Metric C2 = Changes in asset location | WMSA: 'Reported location', 'date/time' | GE WMSA data set | Calculated: Changes in reported location between two sets of date/time |
|       | Metric C3 = Asset contents | UAS Data: 'Asset contents', 'case' | GE WMSA data set | Alphanumeric: Asset contents |
|       | Metric C4 = Items removed | UAS Data: 'Asset contents', 'date/time' | GE WMSA data set | Calculated: Items removed = asset contents between two given date/time |
|       | Metric C5 = Asset condition | UAS Data: 'Intact', 'not intact', 'vibration threshold', 'humidity threshold' | 11/11/2019 UAS | Binary: 'Intact', 'not intact', 'vibration threshold exceeded', 'humidity threshold exceeded' |
| D. Business impact metrics | Metric D1 = Condition assessment | WMSA: 'humidity', 'humidity limit exceeded', 'operable condition' | GE WMSA data set | Calculated: Condition assessment = Number of cases exceeding humidity limit |
|       | Metric D2 = Lift cost | WMSA: 'Expected location', 'actual location', 'activity plan' | GE WMSA data set | Calculated: Lift cost = Expected location versus actual location, activity plan cost |
|       | Metric D3 = Storage footprint | WMSA: 'Maximum storage capacity', 'occupied storage capacity' | GE WMSA data set | Calculated: Storage footprint = Maximum storage capacity − occupied storage capacity |
|       | Metric D4 = Work package assembly time | WMSA: 'Parts requested', 'arrival date', 'departure date', 'ETA', 'ETD', 'date/time' | GE WMSA data set | Calculated: WPAT = [Arrival date/time - ETA], and Departure delay = [Departure date/time - ETD] by location |
|       | Metric D5 = Inventory | WMSA: 'Tracked parts' | GE WMSA data set | Calculated: 'Number of tracked parts' |
|       | Metric D6 = Storage inventory | WMSA: 'Part requested', 'time to locate part' | GE WMSA data set | Calculated: Storage inventory = Time to locate part requested |
| E. Sustainability metrics | Metric E1 = Logistics cost | WMSA: 'Transport cost', 'warehousing cost', 'inventory carrying cost', 'administration cost' | New metric proposed - WMSA | Calculated: Logistics cost = Transport costs before − transport cost after, warehousing costs before − warehousing cost after, inventory carrying costs before − inventory carrying cost after, administration costs before − administration cost after |
|       | Metric E2 = Loss/damage | WMSA: 'Total cost of damaged goods', 'thefts', 'accidents' | New metric proposed - WMSA | Calculated: Loss/damage = Total cost of damaged goods, thefts and accidents |
|       | Metric E3 = Safety | WMSA: 'Reported incidents' | New metric proposed - WMSA | Number: Number of reported incidents directly involving the new system |

(continued on next page)
| Source | Metric | Data element | Data source | Data type |
|--------|--------|--------------|-------------|-----------|
|        | Metric E4 = Acceptance | WMSA: ‘Socio-economic acceptance’, ‘market acceptance’, ‘community acceptance’, ‘trust’, ‘do not trust’ | New metric proposed - WMSA | Binary: Acceptance = ‘Trust’, ‘do not trust’ |
|        | Metric F1 = Technology adequacy responsiveness | UAS Data: ‘Connection’, ‘no connection’, ‘bad connection’, ‘stable connection’ | New metric proposed: WMSA GE WMSA data set 11/19/2019 | Binary: ‘Connection’, ‘no connection’, ‘bad connection’, ‘stable connection’ |

<sup>* New metrics.</sup>
