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Implementing Grain Traceability Standards: CART and Simulation

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ABSTRACT. ***To ensure food safety, food manufacturers need the ability to quickly identify and trace food products to all equipment and processes throughout the entire associated food supply, production, and transportation network. Government and industry have recognized that supply chain traceability is the key to keeping the public safe, but new information standards are needed to enable such traceability. This paper describes several efforts being undertaken by industry, government, and academic organizations to develop and standardize traceability technology, focusing on grain traceability, and how modeling, simulation, and analysis technology are being used to support these projects. Noteworthy among these efforts is AgGateway's Commodity Automation by Rail and Truck (CART) project, which sought to understand the business processes and data exchanges required, all the way from farm operations through grain elevators to receiving at a feed manufacturer; exploring solutions through small proof-of-concept (PoC) projects; and enhancing and implementing existing standards, primarily the ISO 11783 standard for farm machinery electronics, and the AgXML standard for grain data exchange. The paper also presents ongoing work on using agent-based simulation to validate proposed traceability standards.***

Keywords. agent-based simulation, food traceability, standardization, supply chain analysis.

Introduction

Negative impacts to the food supply chains can be extremely costly, having caused over $22 billion in losses due to food recalls and related expenses (Hussain and Dawson, 2013). They can also be dangerous, having caused over 8.9 million illnesses, 53,245 hospitalizations, and over 2300 deaths (Flynn, 2014; ERS, 2017). Managing the supply chain for complex products such as cars or airplanes is difficult and might involve millions of parts from dozens of suppliers. Managing the supply/production chain in the food manufacturing domain adds a unique characteristic of both the input materials and the final product: they are biologically-based and thus perishable; they are usable during a limited timespan. This requires special procedures for gathering, storing, handling, and transporting materials and end-products, making the logistics for input sourcing and end-product distribution complex, costly, and susceptible to a myriad of disturbances including adverse weather

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conditions and transportation worker strikes.

There is constant variability in the characteristics of food production input materials. In addition, vast differences can be observed in the material characteristics of a product across lots, even from the same year. This forces manufacturers to constantly test, monitor, and find alternate sources for their input materials and then modify their products' manufacturing processes based on the characteristics of the materials that they were able to source.

To help manage the complexity of the food supply production chain and to deal with adverse events when they occur, most participants in the supply production chain have traceability-enabling systems. Briefly, traceability is "the ability to track any food through all stages of production, processing and distribution" (European Commission, 2017). Unfortunately, there is no standard for traceability systems or their information content that covers the complete food production chain. Furthermore, at many points in the supply chain, traceability information is collected and recorded manually and maintained on physical records, severely limiting the speed with which the information can be accessed when needed.

A system providing end-to-end traceability would enable the discovery and use of synergies in the food production chain; this would lead to a more efficient and cost-effective supply and production system; and would enable that problems be addressed quickly and with a minimum effort. The need for such a system has been recognized; many companies work to improve traceability within their organizations (Church, 2015; Dow, 2018) and academic researchers are studying various aspects of the traceability problem (Thakur and Hurburgh, 2009). Through the passage of the Food Safety Modernization Act (FSMA; US FDA, 2018) the U.S. government has mandated basic procedures that stakeholders in the food production and supply chain must follow, but because a standard system to support traceability does not exist, dates for strict compliance with FSMA have been delayed (Schultz, 2018).

To move towards the goal of a standards-based system supporting end-to-end traceability, several organizations have efforts underway to address traceability related deficiencies in the current food supply production chain. This paper describes several of these efforts, emphasizing how modeling, simulation, and analysis technology can help reach the desired goals. The technical developments needed to support end-to-end traceability are also discussed, as well as how the results of current traceability research efforts will be coordinated to support future efforts.

Key Notions of Traceability

The UN definition of traceability, "The ability to identify and trace the history, distribution, location and application of products, parts and materials…", points to a key function of traceability systems: *trace back* (UN, 2014). Trace back is the ability to assemble, for a given product, information about the input materials, processes, and human or machine resources that were directly used to create the product, and then to recursively repeat that process for each of the materials, processes, and/or human and machine resources discovered. This process is extremely important when trying to uncover the time, location, and nature of the adverse event in the production chain that caused a product defect.

A complement to the trace back function of traceability systems is the ability to *trace forward*. This function seeks to, given a specific material and/or piece of equipment at a specific point in the production chain, identify the materials at the next step in the production chain that used the previous materials as inputs or used the associated equipment in its processing, repeating this process recursively until all end products that are directly or indirectly related to the initial material or equipment have been identified. The trace forward function is necessary to identify the scope of potential end-products affected once the root cause and origin of a product defect has been determined.

One problem that makes traceability difficult is that different partners in the supply/production chain might use different management and/or computer systems to carry out their operations, and these systems might use different information to identify or describe the same product or material. Some kinds of traceability analyses only look at information describing how products move between partners; others focus on each traceability-related activity that happens within a partner's organizational boundary. Issues, information, and analysis focused on the inter-partner production chain activities are referred to as being a part of *external traceability* while issues, information, and analysis focused on what happens within a partner's organizational boundary are referred to as being a part of *internal traceability*.

The information necessary to support a traceability system is complex, interrelated, and vast; making sense of it can be very challenging. Even though a clear goal of a traceability system is to be able to associate a product with its inputs, the current approach most widely used to organize traceability information focuses on the events that occur within a production chain that will enable product inputs and outputs to be traced. With this approach, *Critical Tracking Events* (or CTEs) are defined to contain data about the input and output materials, processes, locations, and human or machine resources associated with each event in the production chain that is necessary to support the trace forward and trace back functions of a traceability system (Badia-Melis et al., 2015).

Using CTEs as the basis for recording, managing, and analyzing production chain data has been shown to enable supporting traceability analyses related to external traceability, internal traceability, and analyses which include both internal and external elements.

Barriers to the Development of Traceability Systems for Bulk Grain

The continued occurrence of food safety incidents has only underscored the need for traceability systems that can quickly perform trace back and trace forward functions to limit the exposure of consumers to serious illnesses and possible death. Developing and deploying such systems present a variety of problems. Developing systems to support production chains that have bulk grain as one of its materials add to those problems; some specific challenges are detailed below.

Difficulties in conceptualizing an end-to-end traceability system

Since no end-to-end traceability system currently exists, it is difficult to even discuss the concept of such a system with many production chain partners. Partners may have only focused on the internal traceability issues of their organizations and much of that information may only be maintained as tribal knowledge within the organization. Also, efforts to support external traceability may be limited to providing “one-up, one-down” traceability for themselves and their direct production chain partners (Bhatt et al., 2013).

No standard promoting consistency in the representation and interpretation of traceability information

In general, each participant in a production chain has their own unique enterprise and operational infrastructure. Traceability system components will need to be built upon the different infrastructural components of each partner, and mechanisms are needed to provide consistency and reduce or eliminate ambiguity in the information created and exchanged within the production chain. First, there is a need to standardize how to represent the data describing traceability concepts like events, materials, resources, and processes. Second, there is a need to provide context given that the same term may be interpreted differently by different production chain participants. This becomes evident by observing that the term “lot” could refer to a bag of grain, a truckload of grain, a rail car full of grain, of even a portion of land on which grain is grown.

Lack of methods for assessing relationships between input and output grain lots passing through grain storage bins

In production chains involving grains such as wheat or corn, the grain is often stored in large containers referred to as *bins* or *silos*. In general, these bins operate like queues: grain enters through the top and comes out of the bottom. Unfortunately, due to many factors (e.g., bin geometry, type of grain, grain moisture content, and extraction method) problems such as doming and rat-holing cause the grain movement through the bin to diverge from a strict first-in, first-out material movement pattern. In order to assess which bin outputs are connected with specific bin inputs, methods need to be developed to characterize how movement through a bin is affected by bin geometry and/or bin environmental conditions.

No methods for evaluating proposed solutions for defining, exchanging, and analyzing traceability information

As candidate solutions for the aforementioned problems are developed, methods must be developed to assess whether traceability system based on these solutions would operate acceptably before the solutions are deployed.

Addressing Traceability Needs for Production Chains Involving Bulk Grains

The need for systems, methods, and standards to enable the deployment of traceability systems has been recognized by government, academic organizations, and the stakeholders in the food production chain, both in the U.S. and abroad (Donnelly and Thakur, 2010; Thakur et al., 2009; Opara, 2003). The motivation for feasible, economical, standards-based solutions for traceability has recently increased due to the lack of solutions that stakeholders in the U.S food production chain can use to comply with the precepts of FSMA. Several academic, government, and industry organizations, which were individually working on different aspects of the problem for production chains involving bulk grains, have recently begun to work together to develop methods and information specifications for traceability systems that might lead to standardized traceability solutions. While this is not an official “project”, these organizations hope that collaborating will result in synergy and lead to deployable results for each of their efforts. Several of these efforts are described below.

Modeling processes and their data: BPMN and Transfer Event modeling

Enabling all stakeholders to understand the complexities of an extensive production chain is a difficult but necessary task. Often, information about a process early in the chain must be collected and maintained to enable the ability to trace back from a downstream process. To illustrate how each production chain stakeholder’s processes interact, participants in the AgGateway industry consortium’s interoperability projects have been using Business Process Model and Notation (BPMN; Silver, 2011) to model the production chain (AgGateway, 2017). They were joined in this effort by researchers from the Open Applications Group Quality Content work group and from the NIST Agri-food Manufacturing System and Supply Chain Integration project, who have been doing similar modeling for supply and production chains in other domains. This collaboration involved modeling the overall production chain and key processes along it (OAGi, 2016; NIST 2017). As an example, Figure 1 presents a BPMN diagram that illustrates the harvesting process for bulk grain, created using a web-based BPMN modeling tool (Trisotech, 2018).

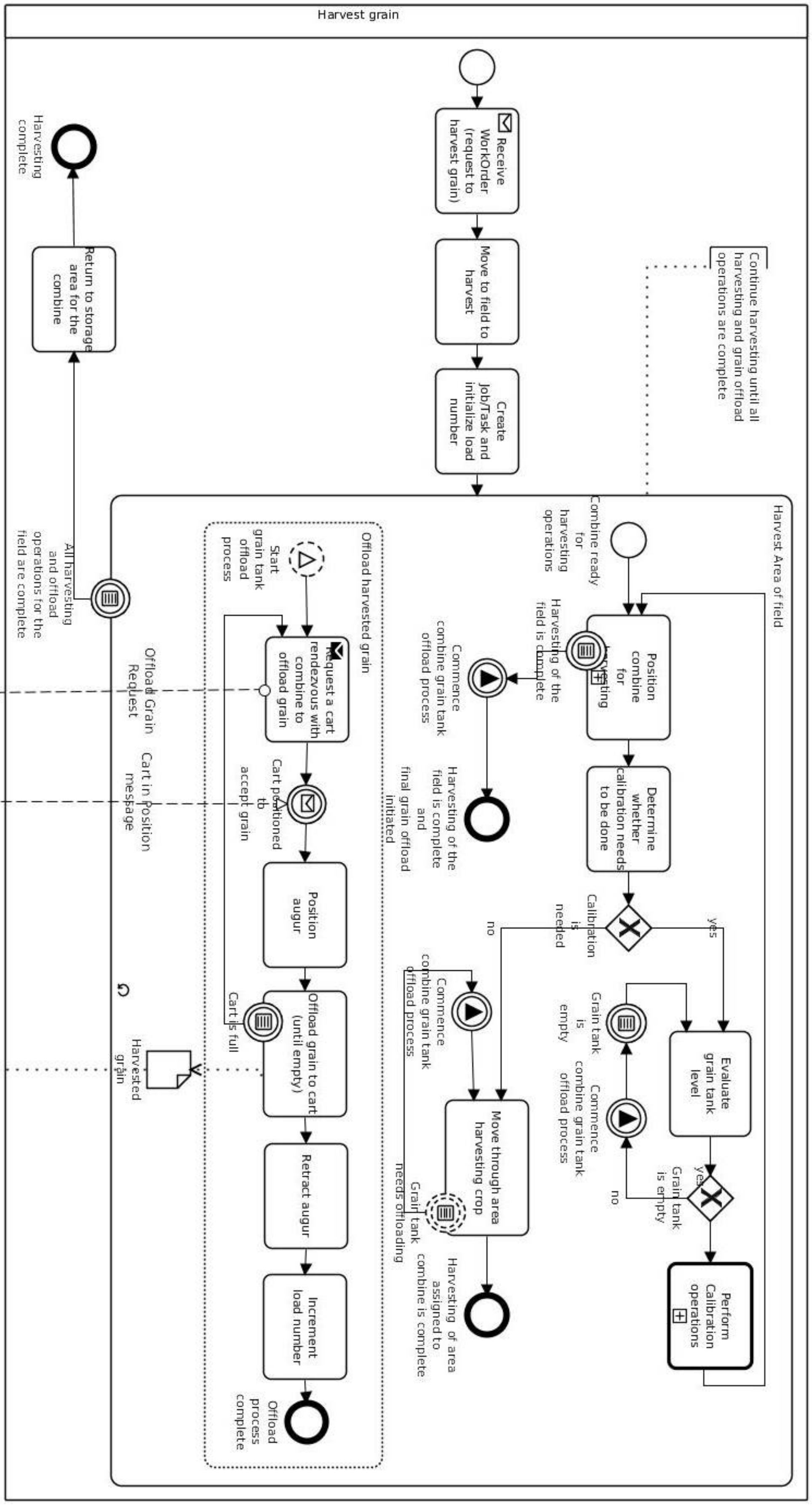


Figure 1: BPMN process model of a grain harvest, including subprocesses for harvesting an area of the field and

offloading grain to a cart.

The data elements that describe the depicted processes were established and documented using BPMN diagrams of key production chain processes as a guide. With respect to support for traceability, it was decided that the focus should be on the critical tracking events and supporting data elements that document the transfer of quantities of grain from one container to another. Figure 2 shows how such a CTE named *TransferEvent* could be represented as an extension of the AgXML standard (AgXML, 2009) which defines information entities that can be used to exchange data between grain production chain partners.

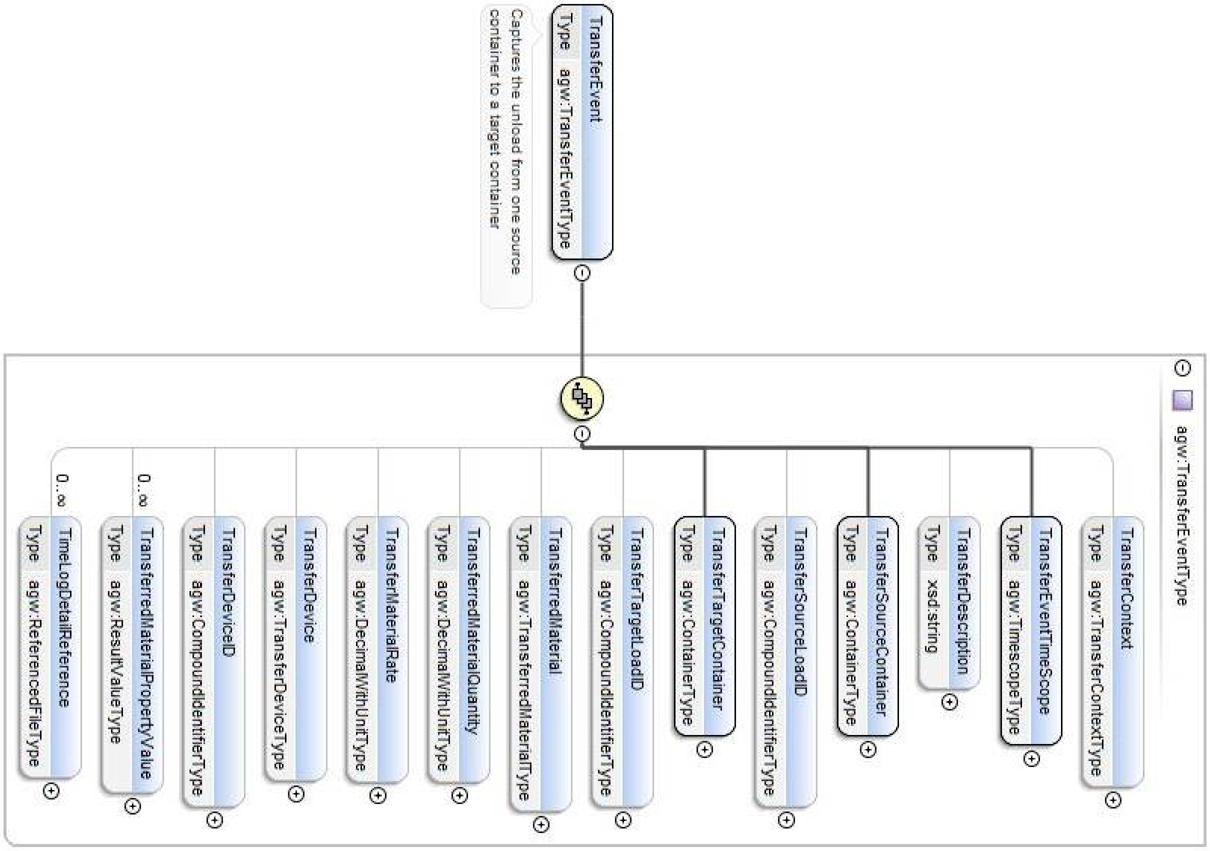


Figure 2: TransferEvent as an extension to AgXML

AgGateway Commodity Automation for Rail & Truck (CART) Project Proof of Concept (POC)

To overcome deficiencies in the hardware, software, and data storage and exchange systems available to support production chain traceability and information exchange automation, AgGateway, an industry consortium with 200+ members, dedicated to enabling digital agriculture, started a project called the Commodity Automation for Rail & Truck (CART) project. The stated goal of CART is to facilitate “grain traceability from combine to grain cart, to truck, to elevator, to food processor” (AgGateway, 2018). To reach that goal, CART is conducting a number of technology, or proof of concept (POC) demonstrations, to evaluate the feasibility of proposed solutions for traceability. These demonstrations are in fact live simulations as defined by the live, virtual, constructive simulation taxonomy (US DoD, 1998). The POCs involve both modified and unmodified hardware and software, integrated together to collect, store, and exchange traceability information collected during the execution of real grain harvest events. Participants in CART include: farm operators, hardware and software vendors (some of which modified their products to participate in the POC), grain elevator operators, and processors (manufacturers of end-products that use grain as an input). The key processes of the harvest event were illustrated by diagrams such as Figure 1, and the transfer event data was exchanged as specified by the representation depicted in Figure 2. The points in the production chain where TransferEvents are exchanged are depicted in Figure 3.

The POC enabled participants to evaluate many different aspects of the proposed traceability solution, including overall approach feasibility, existing sensor adequacy for raw data collection, proposed hardware and software modification feasibility, and cloud-based solution feasibility for data storage and exchange. Some of the results of the initial POC are:

- The overall approach is feasible;
- TransferEvent data should be adequate to support traceability needs, and;

- Hardware may need to be enhanced with additional automation capabilities and additional hardening to withstand environmental conditions.

Figure 3: Points in the process where TransferEvents are exchanged

More information about the initial POC can be found in AgGateway (2017A). An additional POC is planned for Fall 2018.

Traceability Through Facilities Typified as Multi-Storage-Bin Environments

Facilities such as grain elevators typically have multiple storage bins to hold grain until dispensed for downstream partners in the production chain. With respect to traceability, two challenges commonly occur due to standard operating procedures at such facilities. First, delivered grain may be distributed to multiple bins and typically records documenting which bins received grain and the amount of grain received may not be kept permanently and in a searchable form. Second, there are no methods for tying grain inputs to outputs based on expected bin flow conditions, taking into account environmental (temperature, humidity, etc.), material (grain type, particle size, moisture content, etc.) and bin shape, material, etc.

To address these issues, NIST is funding research at Iowa State University to look into the traceability issues affecting bulk grains. Part of that effort involves analysis of past and current efforts in defining and using CTEs as the basis for supporting traceability. The output of this research has provided input to the efforts for CTE modeling and standardization described in the previous sections. In addition, part of this effort involves analyzing methods for bin flow characterization towards the goal of developing a mathematical model that can tie bin input to outputs. These efforts are in the early stages, the goal is to be able to use the output of this research to enhance capabilities of tools that support bulk grain traceability.

Simulating Production Chain Traceability for Illustration and Analysis

As previously mentioned, current research suggests traceability in production chains would be best supported by defining and maintaining CTE data about the important events that took place due to production chain operations. As with the live simulation events described previously, efforts to verify the feasibility of proposed solutions for traceability need to take place before standardization and deployment of those solutions. To support this type of analysis, data sets need to be constructed containing realistic collections of CTEs covering the operations of all stakeholders in the production chain and adhering to the format and content proposed by those solutions. To verify that a solution could support traceability analysis, CTE data associated with a specific production chain operation could be modified to indicate the occurrence of an adverse event, and then propagated through the production chain until a set of affected end products is identified. Then, trace back and trace forward analysis could be attempted to determine if all affected products, with few false positives, could be identified from the CTE data defined according to the proposed solution.

To be able to evaluate different proposed content specifications for CTE data, researchers at NIST have created a simulation of a bulk grain production chain that can generate CTE data sets. The primary goal is to generate a realistic collection of TransferEvent data, covering all transfers of grain from the field to the processor, to determine the extent to which traceability analysis can identify end-products affected by adverse events in the production chain. Secondary goals are to illustrate how individual stakeholders interact to perform production chain operations, and to provide a means to evaluate how different models of grain flows through storage bins might affect a proposed solution's traceability capabilities.

The simulated scenario is the same as that covered by the POC live simulation presented above: combines harvest grain from a field; when full, each combine offloads its grain to a cart; when a cart is full, it offloads to a truck; when full, a truck will deliver to an elevator where the grain is transferred to a storage bin; when a processor needs grain, it will send a truck to an elevator where grain is offloaded from a storage bin to the truck; this will then deliver to the processor, where grain will be offloaded to the processor's storage bin. Each time grain is moved from one container to another, a TransferEvent record should be created. In this scenario, not only will grain movement between obvious containers generate a TransferEvent (e.g., grain transfer from a combine's storage compartment to a cart's storage compartment) but a combine's harvesting of grain will also generate a TransferEvent – the area of a field from which the grain is harvested is considered a container for traceability purposes. This matches the TransferEvent generation points described in Figure 3. As was the case in the POC, the content for TransferEvents is based on the proposed specification described in Figure 2, although in both cases data for most of the optional fields was not generated. The behavior for the part of the simulation that covers operations from the field up to the loading of the semi-truck adheres to that specified by the diagram in Figure 1.

In addition to gathering information directly from participants in the POC and others involved in production chain operations, preparation for creating the simulation involved analyzing equipment specifications to determine appropriate value ranges for the key equipment characteristics that would be needed to simulate production chain operations. Information about typical farm crop characteristics was gathered from www.usda.gov.

The simulation was created using the AnyLogic software program (AnyLogic, 2018). This software enables the creation of multimethod simulations; the simulation described here was created as a hybrid agent-based and discrete-event simulation. Agents are constructed to represent the behavior of key entities in the scenario being simulated. The current simulation covers harvesting operations from the field to the dispatching of a Truck to an elevator. Agents to cover operation at the elevator and at the processor are currently under development. Details about several of the currently implemented agents can be found in Table 1.

Table 1: Agents and their responsibilities

Agent	Responsibilities	Key attributes
FieldMgr	Based on initialization data: • Create **Combine, Cart, Truck,** and **CropZone** agents • Assign/reassign **Combines** to **CropZones** • Manage how **Trucks** are filled with grain from **Carts** • Provide visualization of the state of harvesting operations	name id myFarm myGrower
CropZone	• A part of a field that is to be harvested by a **Combine** • CropZone is further subdivided into Areas • Areas enable crop conditions (e.g., moisture, quality, or yield potential) to be varied at a sub-**CropZone** level • Area size can be varied depending on the fidelity need for traceability analysis at the field level • Provide a specific location in a **CropZone** where an adverse field condition can be introduced	name id myFarm myGrower myField AreaList: List [0..n] of Area assignedCombine
Combine	• Seize a **CropZone** • Iteratively process each area in a **CropZone** until finished • The time to finish harvesting each area and the amount of grain harvested are determined stochastically • Track the amount of grain harvested • Pause harvesting and request a **Cart** for offloading operations when the **Combine's** hopper is full • Collaborate with **Cart** and **CartHandler** to perform offloading operations • Resume harvesting once the hopper is empty • Request a new **CropZone** to process after finishing the current one if more **CropZones** need harvesting	myFarm myField zoneTransferSpeed (mph): (time necessary to go from one zone to another.) harvestSpeed (bu/sec) movementSpeed (mph) hopperCapacity (bu) curHopperAmount(bu) areaGrainYield (bu/acre) offloadSpeed (bu/sec)
Cart	• Accept grain from **Combines** and, once full, offload it to a **Truck** • Track current grain amount in its storage compartment • Collaborate with **Combine** and **CartHandler** to perform offloading operations from the **Combine** • Collaborate with **Truck** and **CartHandler** to perform offloading operations to the **Truck**	curZone unloadSpeed (bu/sec) movementSpeed (mph) curAmount(bu) curPartner moveToCombineTime MoveToTruckTime
CartHandler	• Accept grain from **Combines** and, once full, offload to a **Truck** • Collaborate with **Combine** and **Cart** to perform offloading operations from the **Combine** • Collaborate with **Truck** and **Cart** to perform offloading operations to the **Truck**	curZone unloadSpeed (bu/sec) curCart curCombine curTruck

Truck	• Collaborate with **Cart** and **CartHandler** to perform offloading operations • Once full, travel to a **Processor** to offload its grain • Return to original location after grain delivery is complete	Name id movementSpeed (mph) curAmount(bu) location

The execution of the simulation takes place by agents carrying out their defined behaviors and through agent interaction. Agent behavior may be defined by a network of interconnected process modeling blocks (e.g., source, sink, or delay). This is typical for discrete-event simulation software. In addition, agent behavior can be defined by timed, message-based, or condition-based transitions between states in a state chart defined for the agent. In this case, specific behaviors are defined in functions written in the Java language-based coding framework of the AnyLogic software package. These functions are executed based on transitions firing or with entering or exiting a state. Figure 4 shows the state chart associated with a Truck agent.

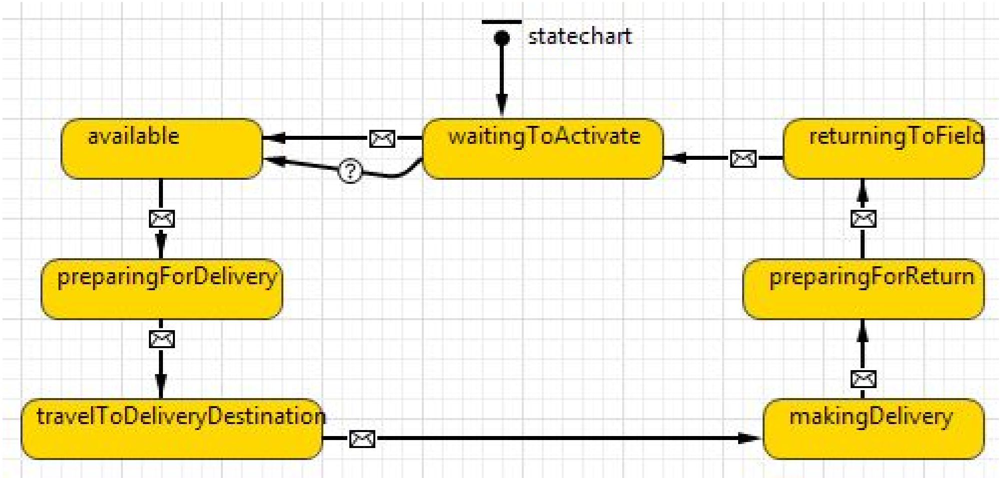


Figure 4: Chart showing the various states for a Truck agent in the simulation. Transitions between states are driven by messages. The truck is initially in a waiting to activate state and then transitions sequentially through the steps required to pick up material to the farm, travel to an elevator, deliver at the elevator and return to the original state to start the cycle again.

This simulation is not intended to provide a realistic emulation of the actual movement of individual vehicles in a harvesting operation. It is based on stochastic variation for the key events, including TransferEvents, that take place during harvesting and operation of the rest of the production chain. This approach: (1) provides a means to produce TransferEvent data sets that enable traceability analysis of the grain movement events in a complex production chain with many participants, and; (2) makes it easier to create simulations of different production chains by just changing the number and initialization data for the agents.

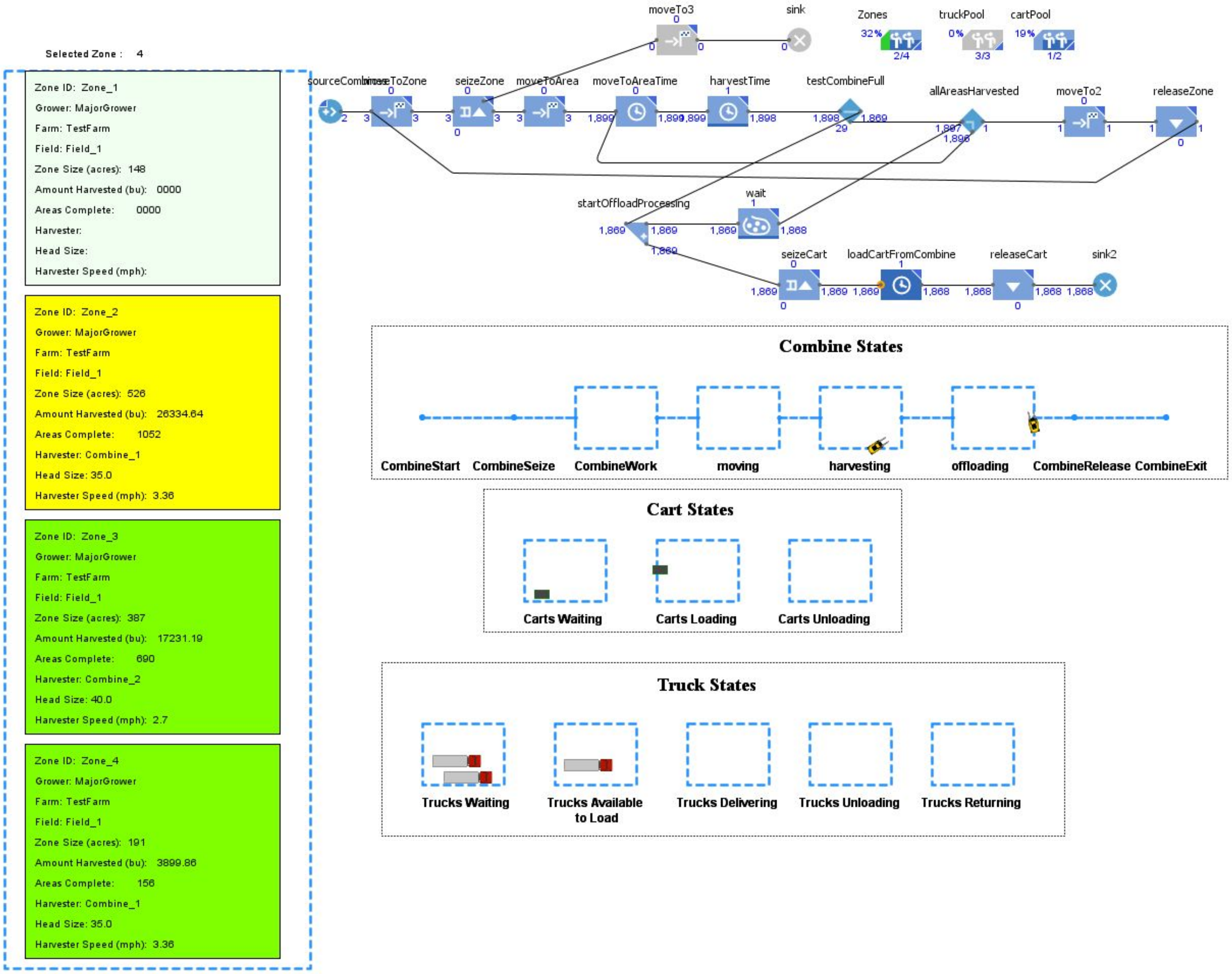
Figure 5 provides a snapshot of a simulation execution with two combines, two carts, three trucks, and four crop zones. The logic that governs a part of the behavior of Combine and Cart agents is presented at the top of the figure. Illustrations for the current states for the Combine, Cart, and Truck agents are provided below that. On the left, the current status for harvesting operations on each CropZone is provided. CropZones for which harvesting has not started, is underway, or has completed are color-coded in light green, medium green, or yellow, respectively. Note that since only two Combines are available, some will have to harvest more than one CropZone. In this case, the combine *Combine_1* was assigned to and finished harvesting cropzone *Zone_2* and is currently harvesting cropzone *Zone_4*.

Summary and Future Work

In this paper, the nature and goals of several projects that are addressing traceability issues have been described. The projects seek to gain synergy through inter-project collaborations, which should both increase the quality and confidence in the outputs of the individual projects. The participants plan to continue to collaborate on areas of common interest. Future activities may include: identification of new stakeholders that can contribute to the different efforts; continued evaluation of the data needs to support traceability; identification and evaluation of existing standards to assess how they might be used to construct systems that support traceability; exploration of whether the development of a cross domain ontology for traceability is feasible, and; finishing work on the modeling of grain flow through a bin.

Analysis of the results of the POC continue, and at least one additional live simulation of the grain production chain is planned, with many new participants showing interest. The target for this effort is Fall 2018.

Immediate plans are to extend the production chain simulation to cover all production chain participants from the farm to the processor. This will enable it to generate a data set of transfer events that can be analyzed that covers the same parts of the production chain as covered by the POC. Future extensions of the simulation include: reading initialization data from and storing results in a database to make it easier to analyze the data; creating a form based front end for the creation of initialization data to reduce the effort to create different production chain scenarios to simulate, and; integrating the result of the bin flow modeling effort once they are available.


Selected Zone : 4

Zone ID: Zone_1
Grower: MajorGrower
Farm: TestFarm
Field: Field_1
Zone Size (acres): 148
Amount Harvested (bu): 0000
Areas Complete: 0000
Harvester:
Head Size:
Harvester Speed (mph):

Zone ID: Zone_2
Grower: MajorGrower
Farm: TestFarm
Field: Field_1
Zone Size (acres): 526
Amount Harvested (bu): 26334.64
Areas Complete: 1052
Harvester: Combine_1
Head Size: 35.0
Harvester Speed (mph): 3.36

Zone ID: Zone_3
Grower: MajorGrower
Farm: TestFarm
Field: Field_1
Zone Size (acres): 387
Amount Harvested (bu): 17231.19
Areas Complete: 690
Harvester: Combine_2
Head Size: 40.0
Harvester Speed (mph): 2.7

Zone ID: Zone_4
Grower: MajorGrower
Farm: TestFarm
Field: Field_1
Zone Size (acres): 191
Amount Harvested (bu): 3899.86
Areas Complete: 156
Harvester: Combine_1
Head Size: 35.0
Harvester Speed (mph): 3.36

Figure 5: Snapshot of graphics that illustrate the simulation including (going clockwise, starting from top right): a graph illustrating a portion of the logic governing the behavior of the Combine and Cart agents; (below that) three shapes illustrating major states for Combine agents, Cart agents, and Truck agents respectively, with icons indicating the agents in the simulation in those states; and (on the left side) CropZones and the current states of those zones in the simulation with different colors: white [or light green] for harvesting not started, yellow for harvesting underway, and medium green for harvesting completed.

Disclaimer

No approval or endorsement of any commercial product by the National Institute of Standards and Technology (NIST) is intended or implied. Certain commercial software systems are identified in this paper to facilitate understanding. Such identification does not imply that these software systems are necessarily the best available for the purpose.

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