

Construction Operation Simulation

Lecture #3

DES engine and hand simulation

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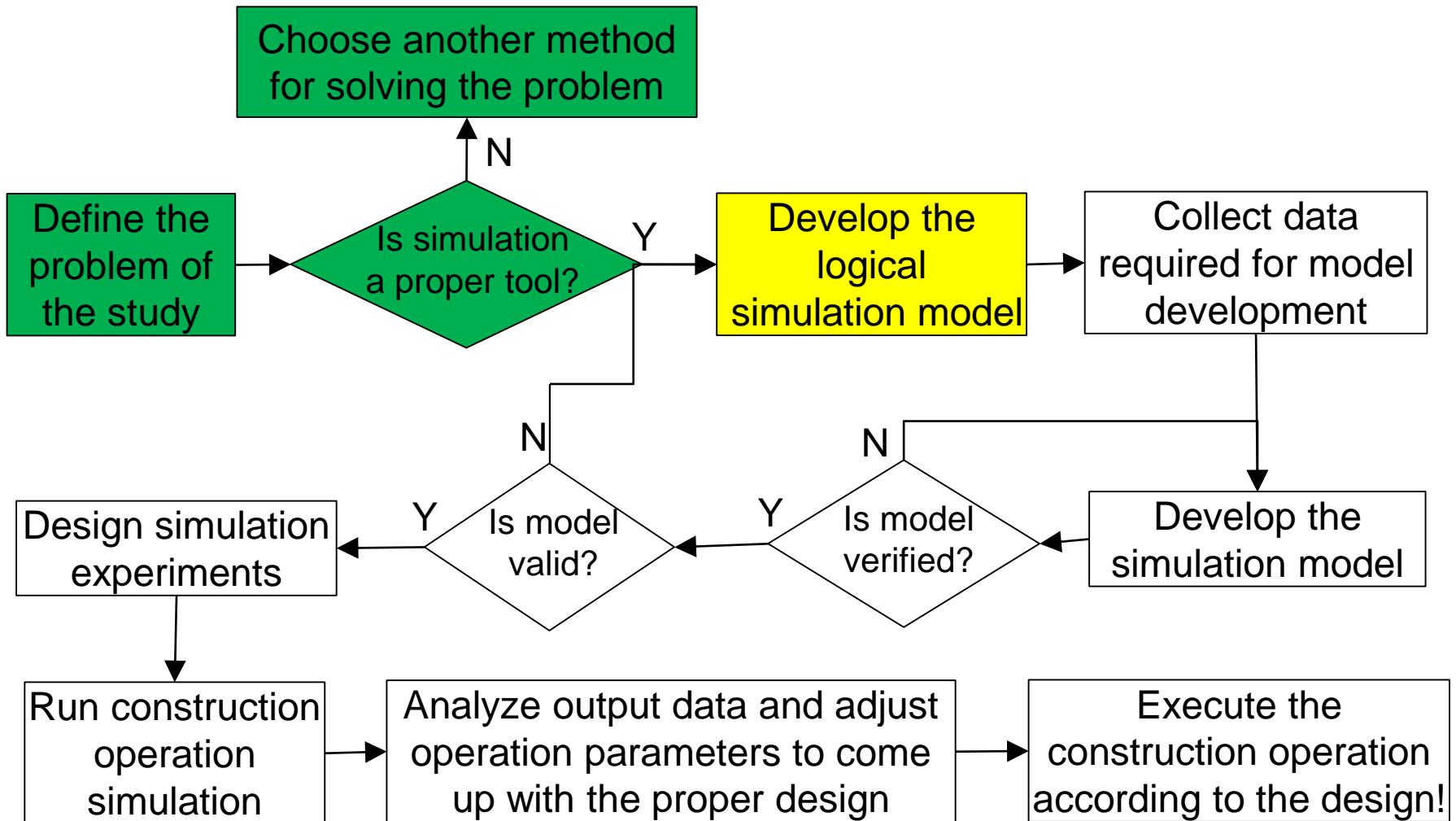
Outline

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- Introduction
- Updating system state
- Simulation engine
- Model initialization
- Event occurrence procedure
- Hand simulation


Main steps in simulation studies

3




Updating system state

4

- So far we have identified DES model elements (entities, resources, activities, events, state variables)!
-  In DES model we are going to imitate system behaviour and updates! Which element can be used for this purpose?

Updating system state

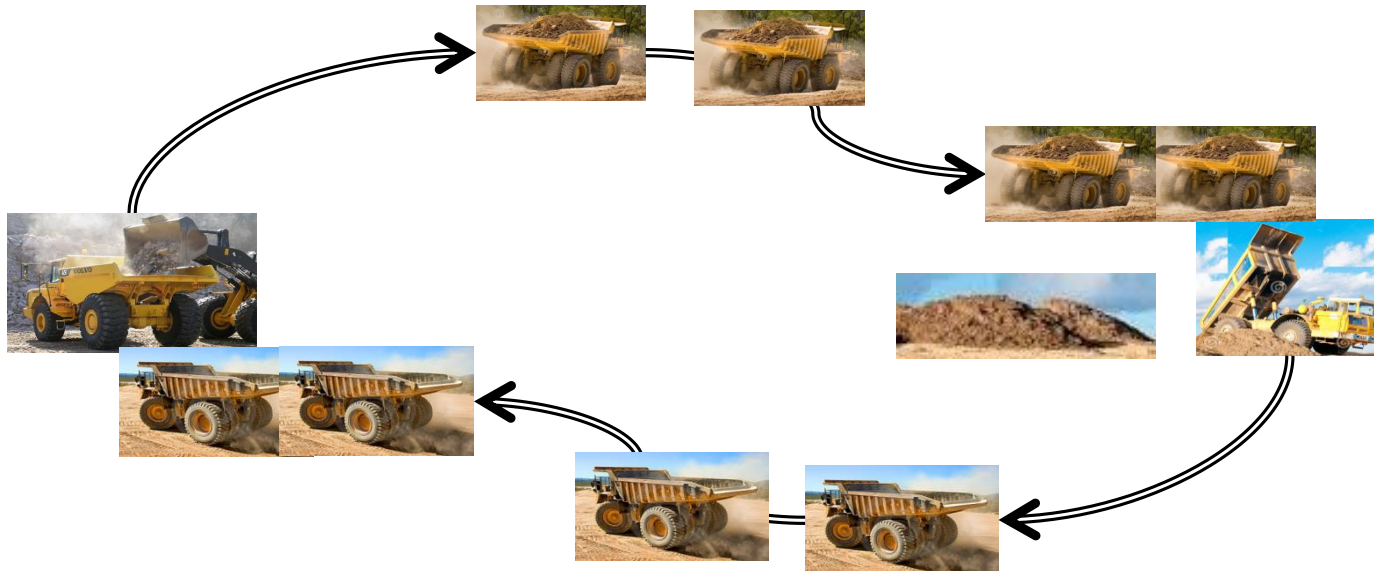
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- So far we have identified DES model elements (entities, resources, activities, events, state variables)!
-  In DES model we are going to imitate system behaviour and updates! Which element can be used for this purpose?
- Event element is our main tool for tracing system behaviour and all updates to the system state over time!
- **Reminder.** System event is an occurrence that changes the state of the system.
- To be able to trace all system updates we need to pick *mutually exclusive* set of events (so called main events) which:
 - 1) Can create all possible system state updates (update all state variables)!
 - 2) Do not have overlaps and duplications in creation of system updates.

Updating system state

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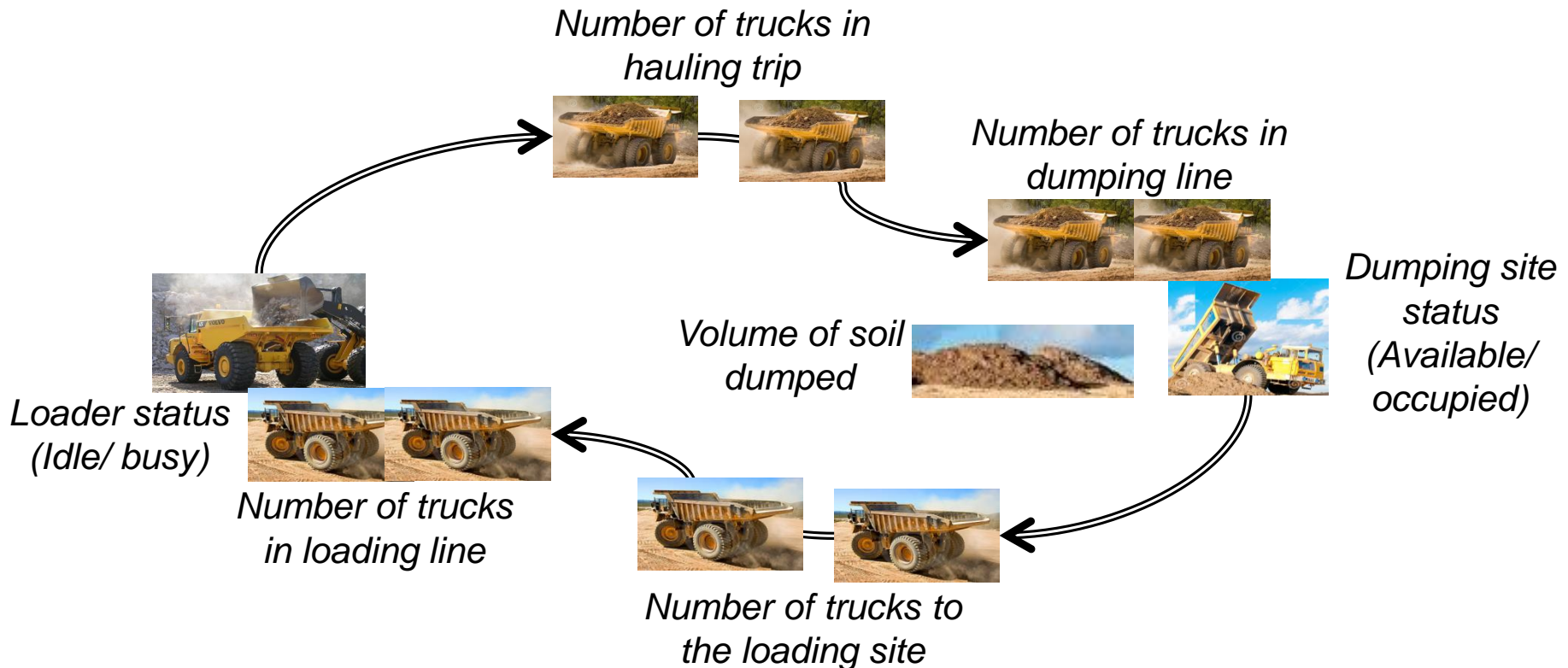
- **Example:** 1) In our earthmoving example we should pick ***set of events which update all state variables***:



Updating system state

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- **Example:** 1) In our earthmoving example we should pick **set of events which update all state variables**:

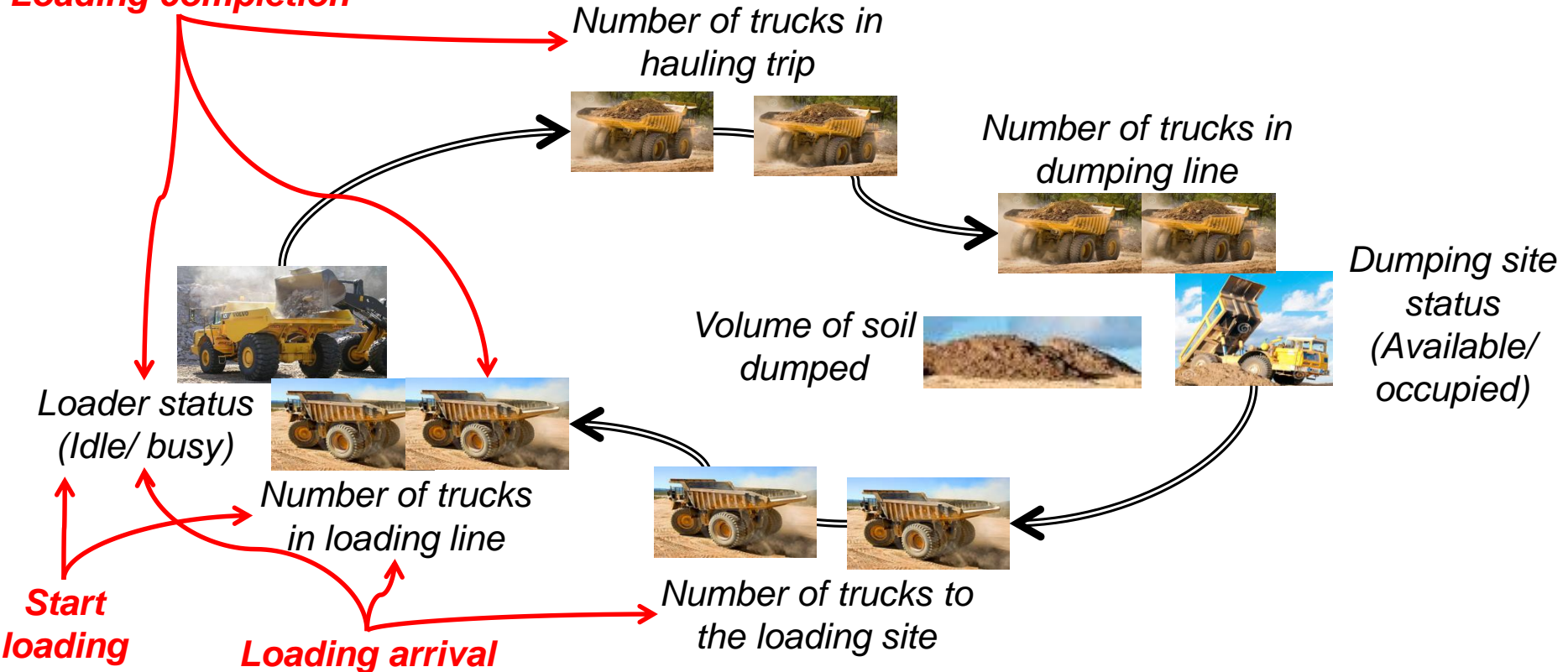


Updating system state

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- **Example:** 1) In our earthmoving example we should pick **set of events which update all state variables**:

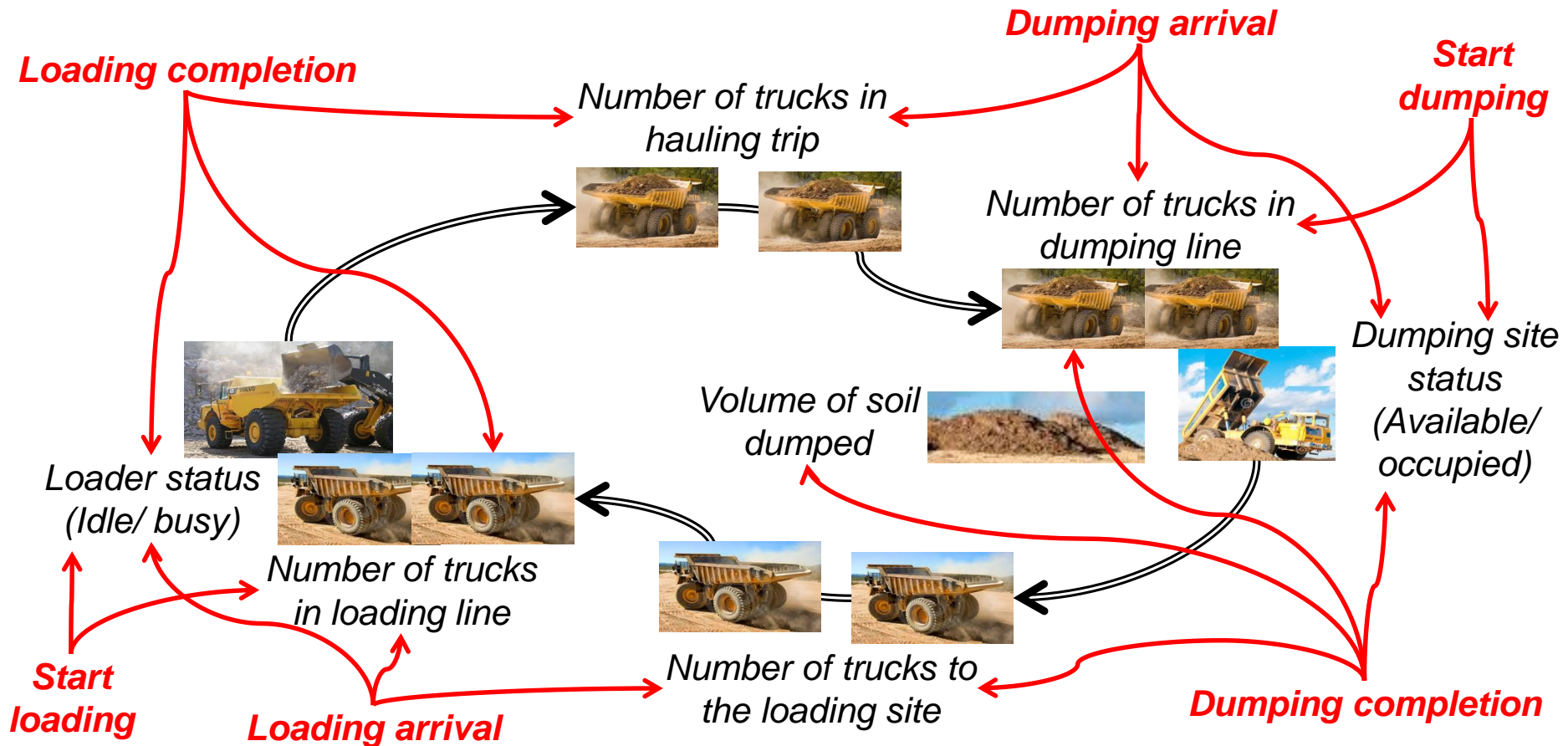
Loading completion



Updating system state

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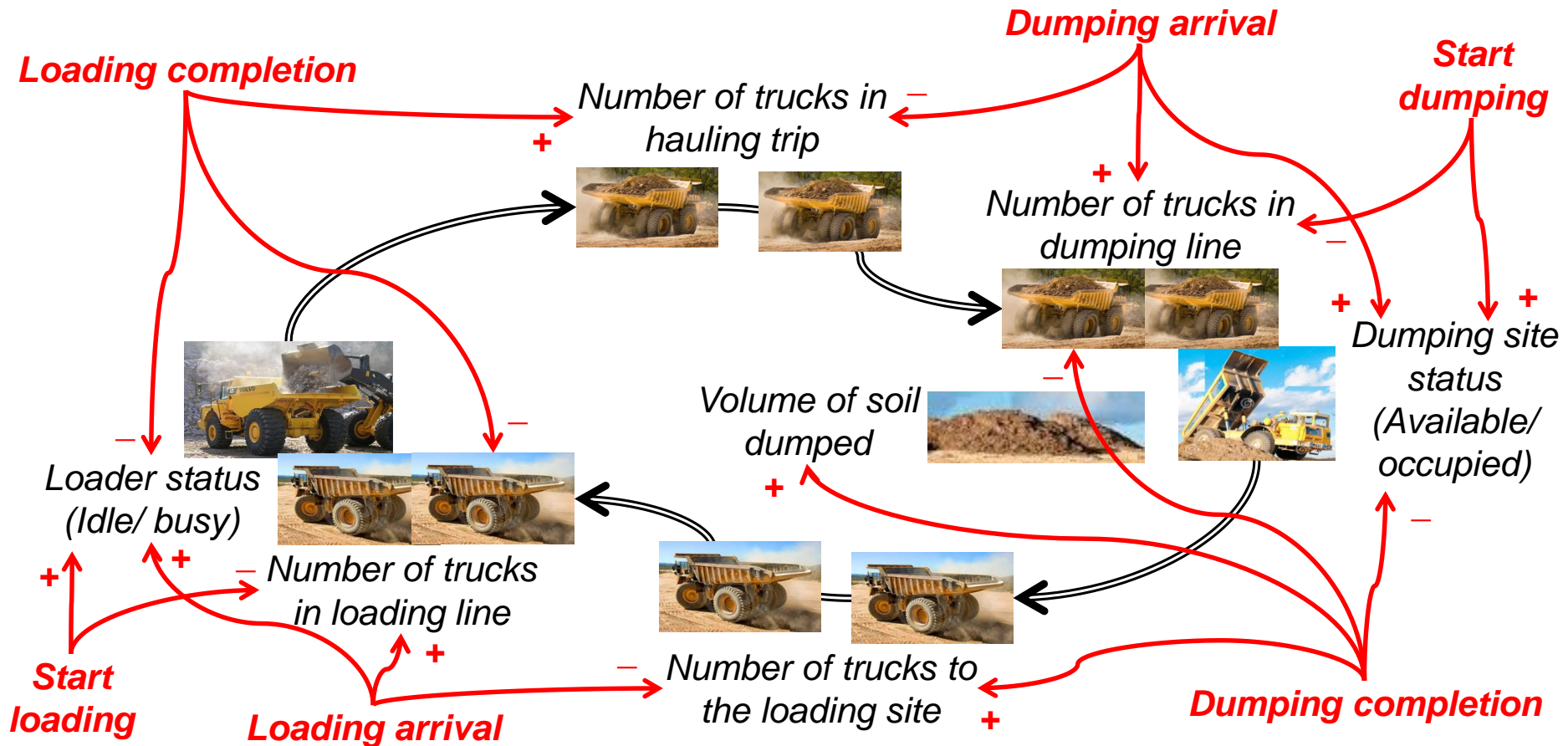
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Updating system state


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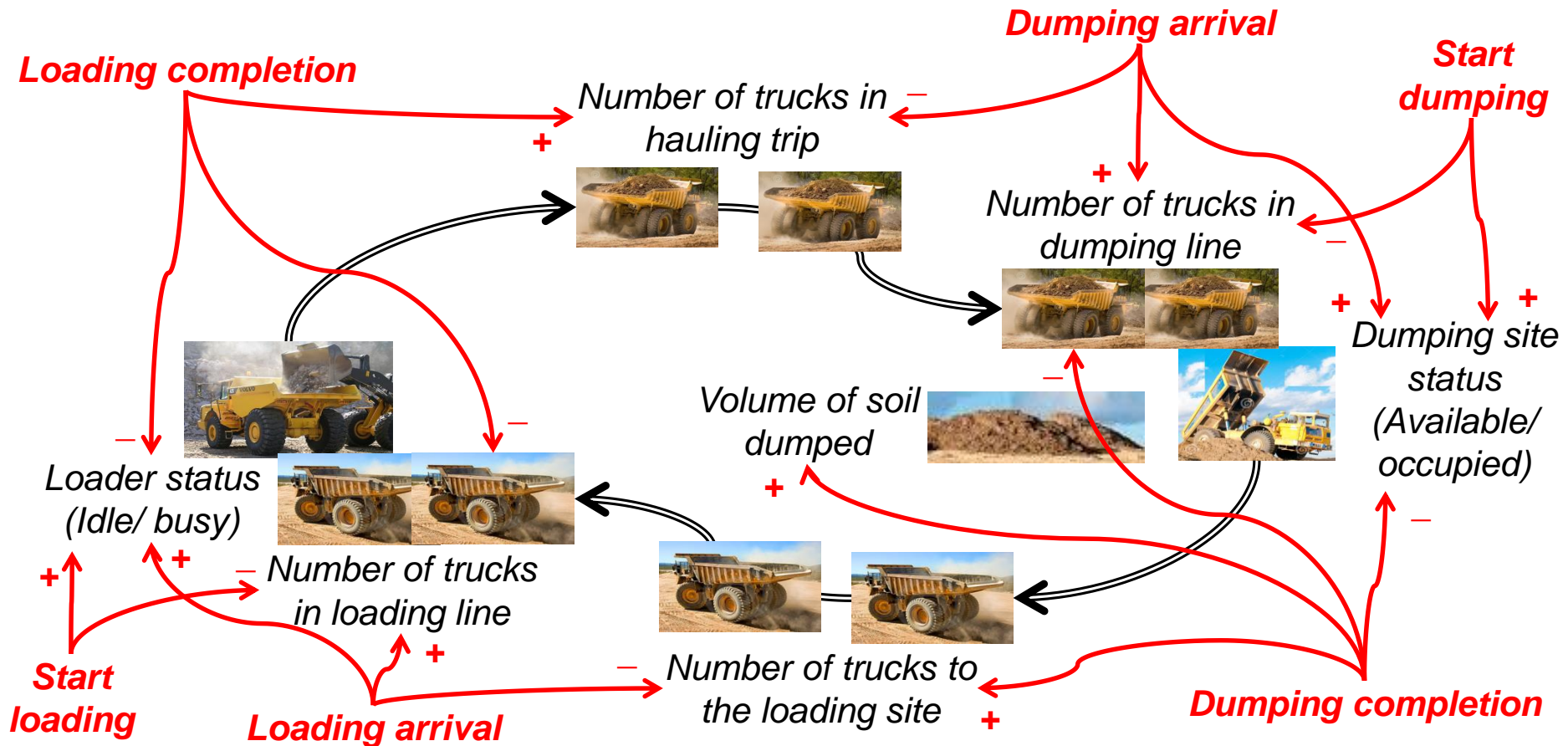
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Updating system state

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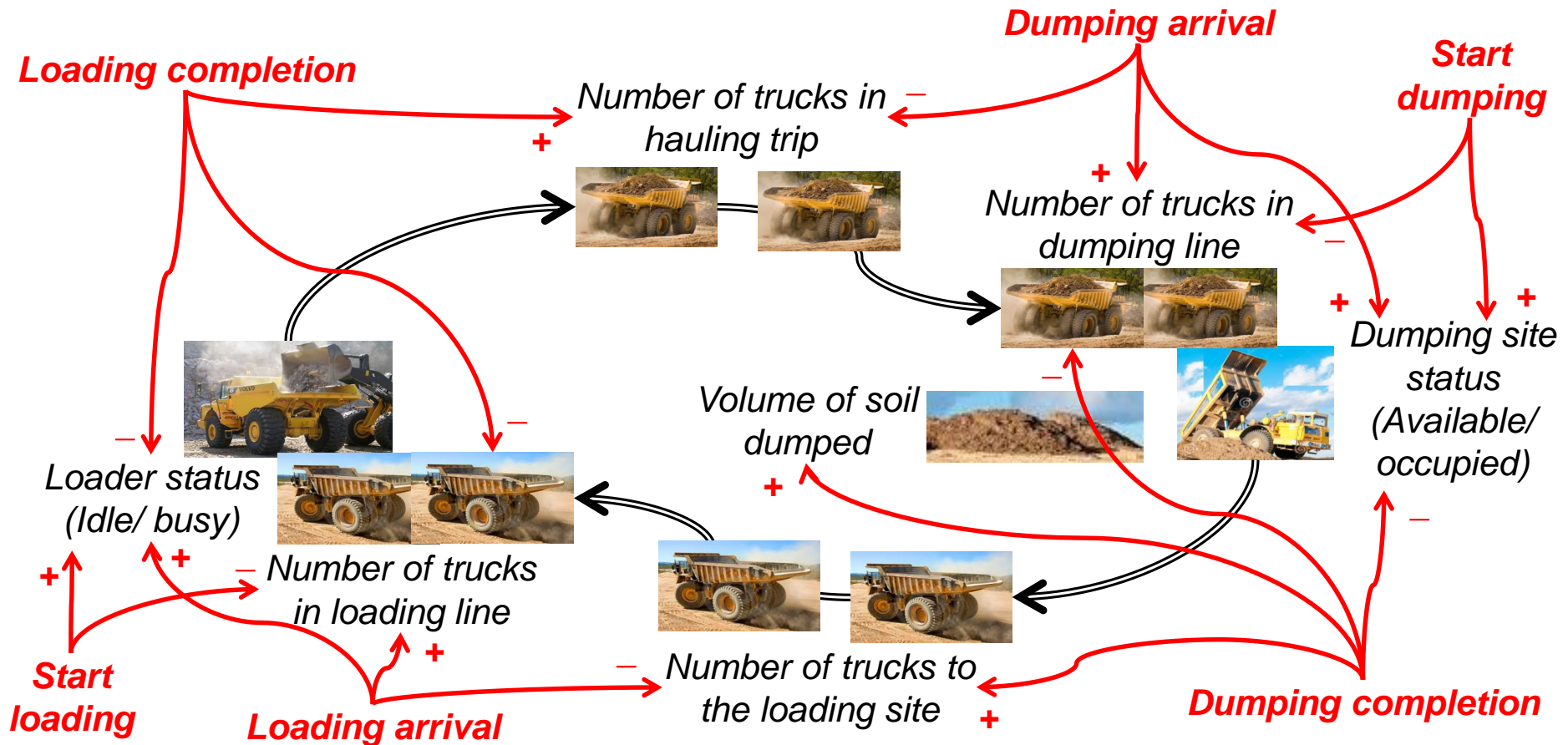
- Example: 1) In our earthmoving example we should pick **set of events which update all state variables**:  Are all related events captured?



Updating system state

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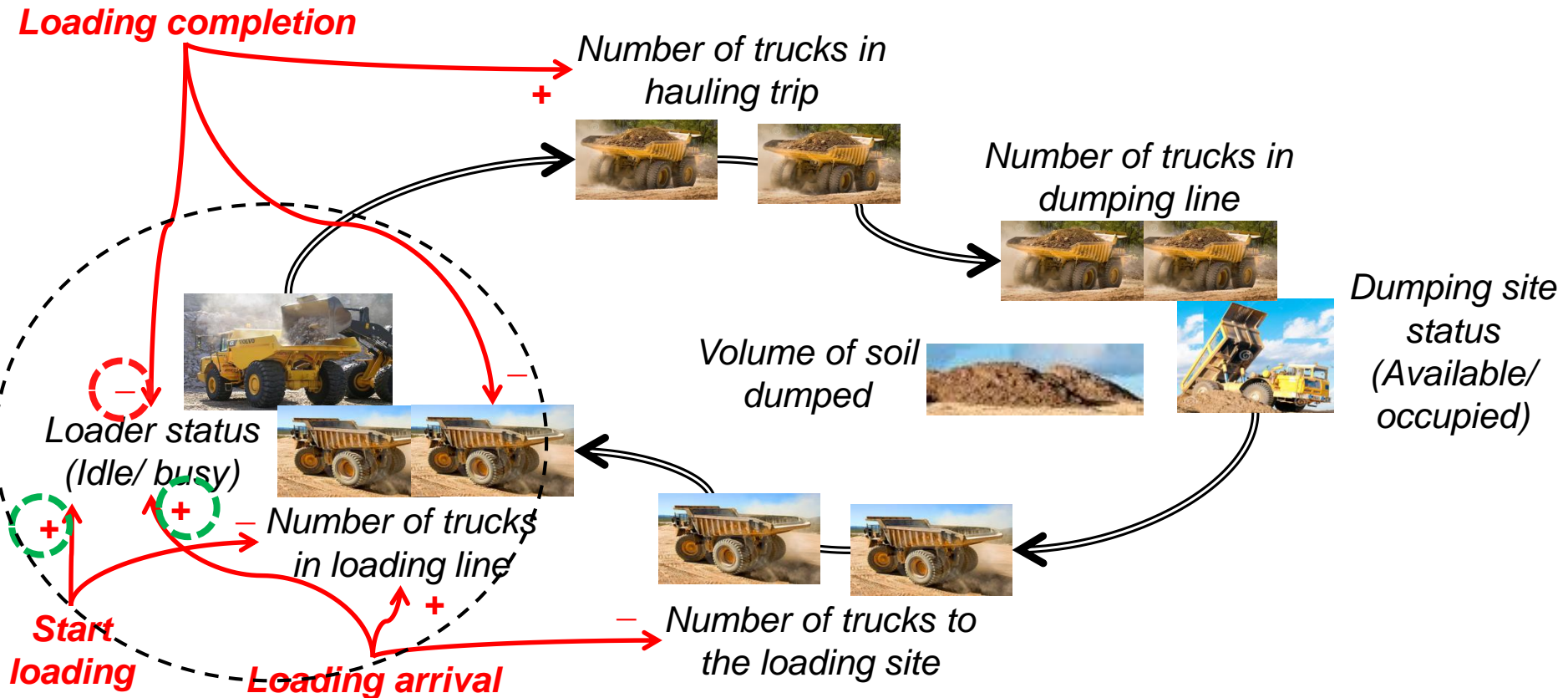
- Example: 2) Avoid **overlaps** and **duplications** in creation of system updates. :



Updating system state

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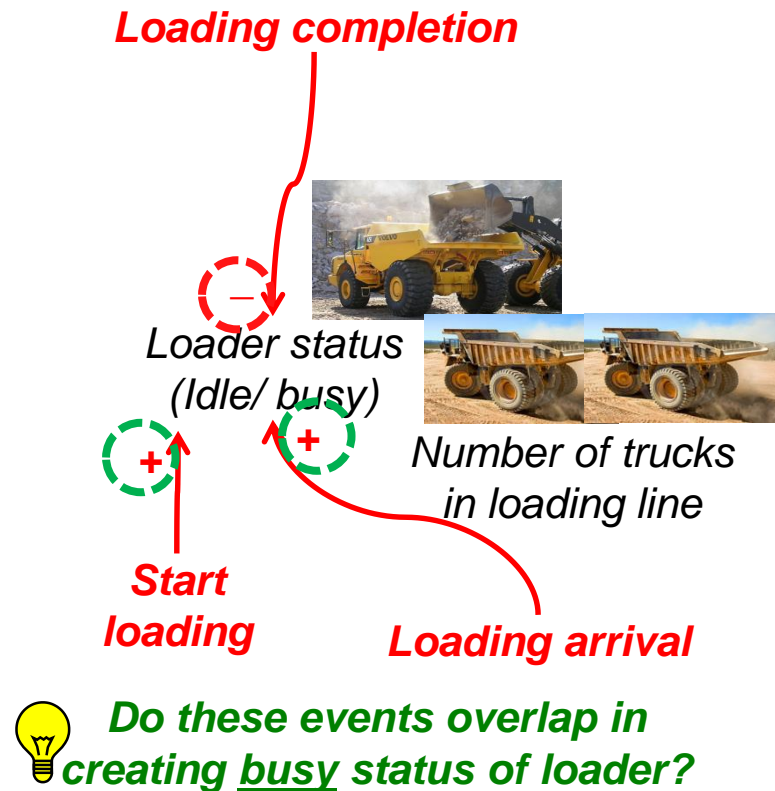
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Updating system state

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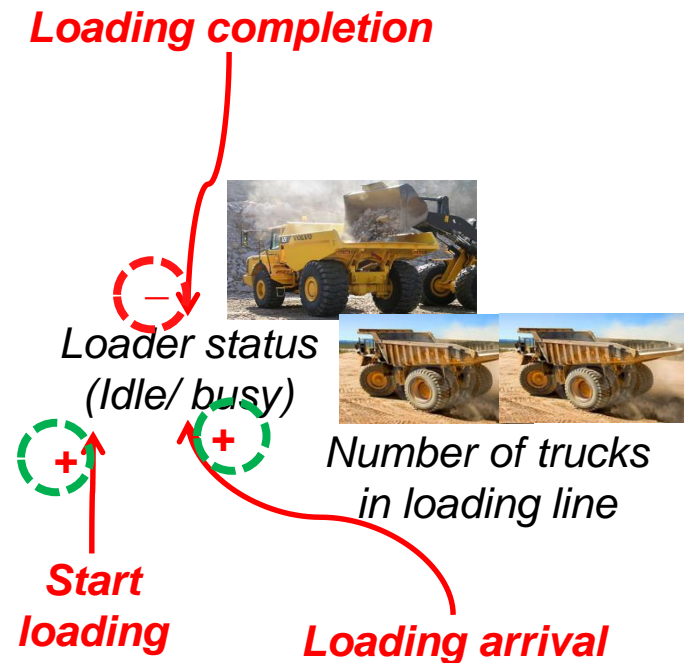
- **Example:** 2) Avoid **overlaps** and **duplications** in creation of system updates. :



Updating system state

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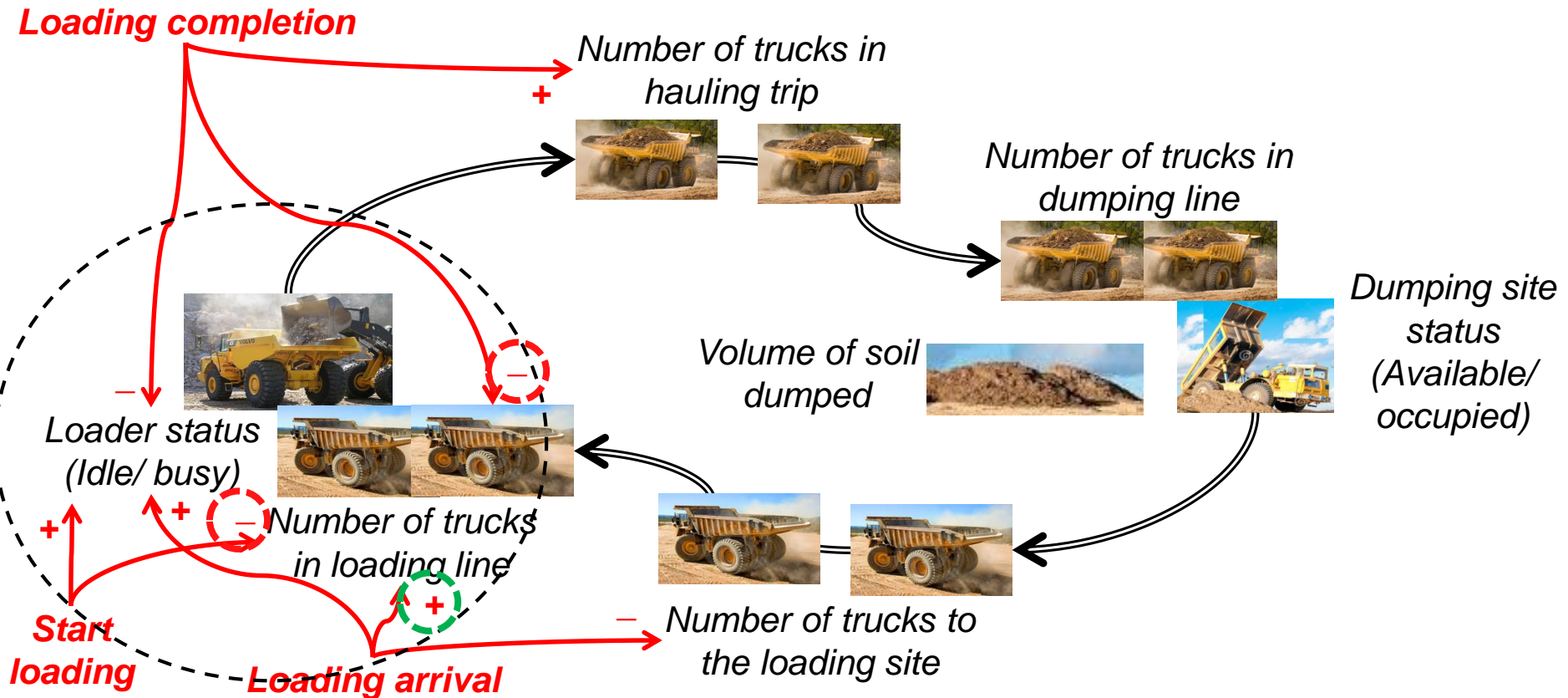
- **Example:** 2) Avoid **overlaps** and **duplications** in creation of system updates. :
 - **Loading** arrival makes loader busy in one ways:
 - 1) After a truck arrival and when loader is idle, loader starts loading
 - **Start loading** makes loader busy in two ways:
 - 1) After a truck arrival and when loader is idle, loader starts loading OR 2) after completion of loading a truck from queue starts loading!



Updating system state

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- Example: 2) Avoid **overlaps** and **duplications** in creation of system updates. :



Updating system state

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- **Example:** 2) Avoid **overlaps** and **duplications** in creation of system updates. :

Do these events overlap in decreasing number of trucks in the line?



Loading completion



Loader status
(Idle/ busy)



Number of trucks
in loading line

**Start
loading**



Loading arrival

Updating system state

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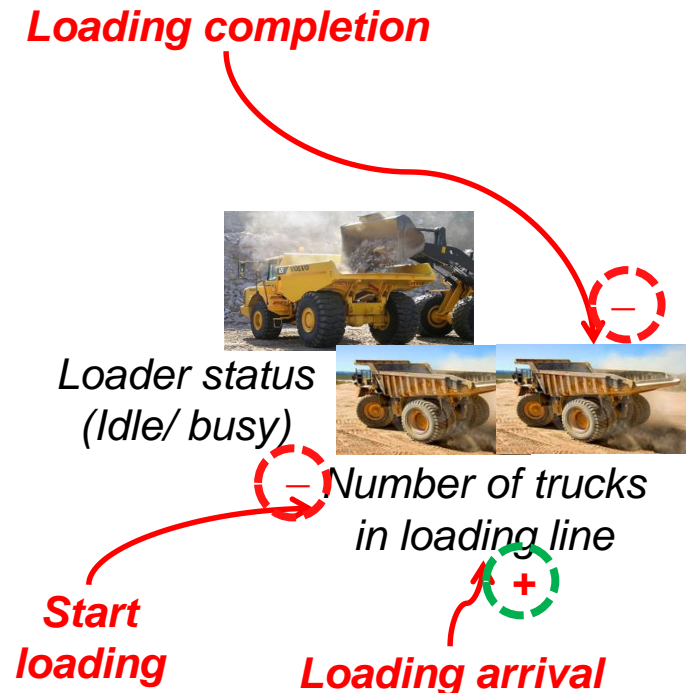
- **Example:** 2) Avoid **overlaps** and **duplications** in creation of system updates. :

- **Loading completion** decreases number of trucks in line in one way:

1) After loading completion a truck from queue starts loading!

- **Start loading** decreases number of trucks in line in one way:

1) After loading completion a truck from queue starts loading!

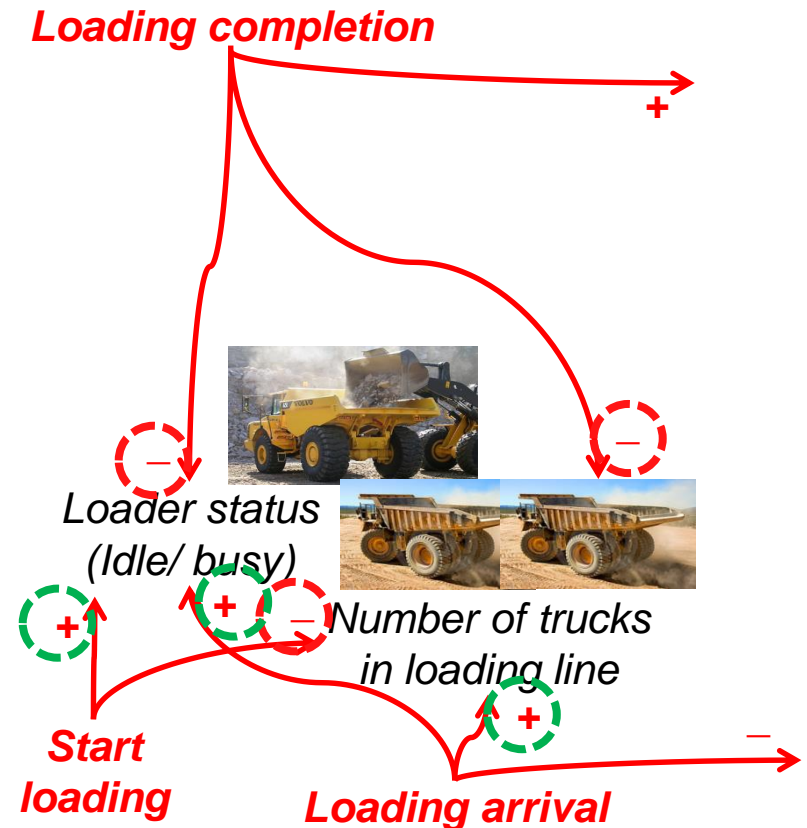


Updating system state

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- **Example:** 2) Avoid **overlaps** and **duplications** in creation of system updates. :

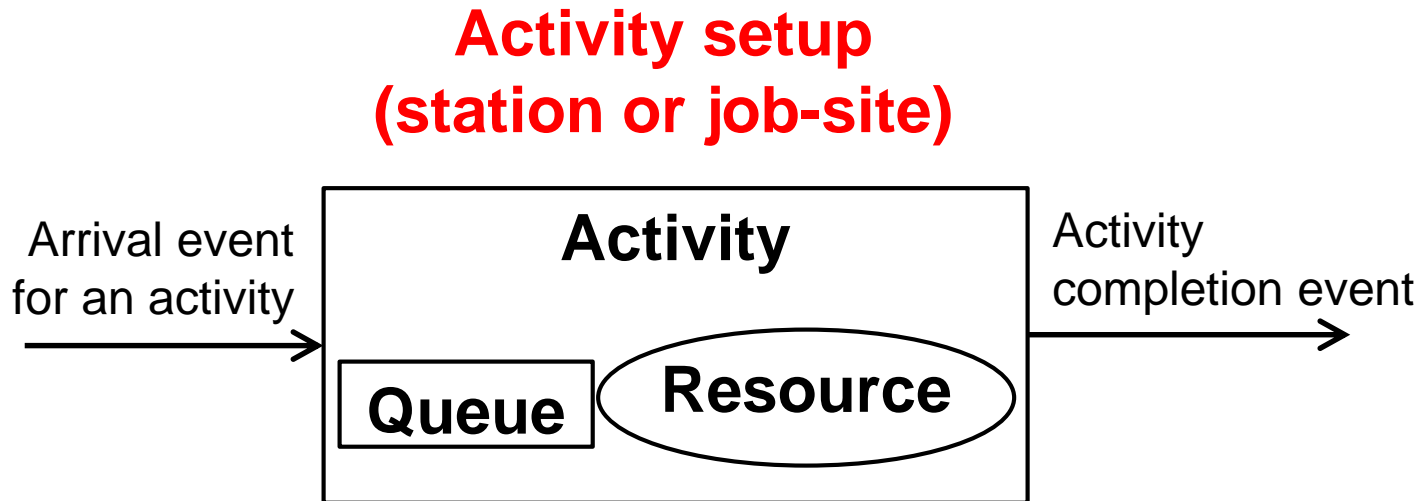
- All system state updates created by **Start loading** event are created by other events, so we can **remove** **Start loading** event from set of selected system activities!



Updating system state

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- What events are selected in general:

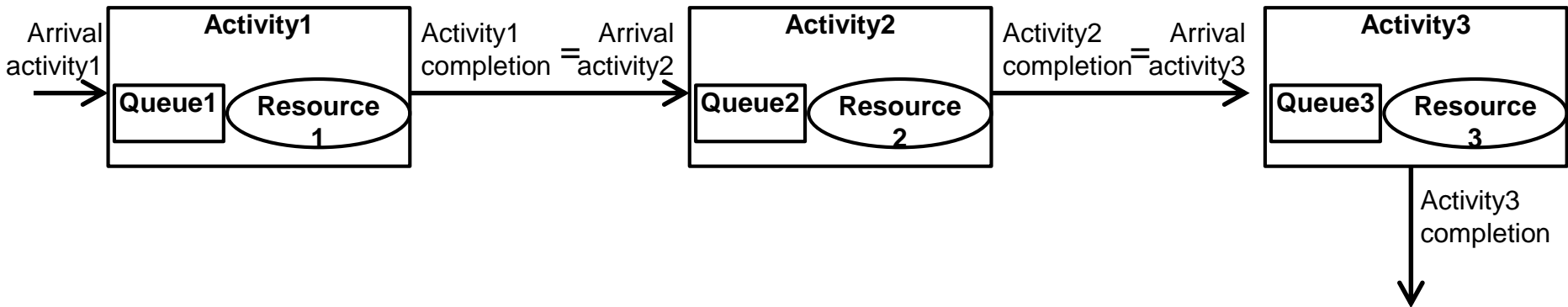


- 🔊 Updates created by middle events (e.g., start activity) are usually addressed by arrival and completion events and can be eliminated!

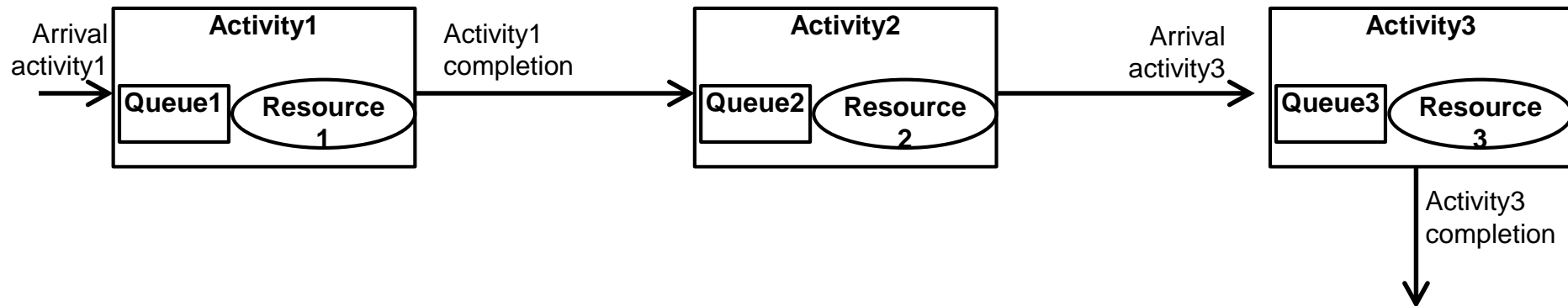
Updating system state

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- Consecutive activities share events:



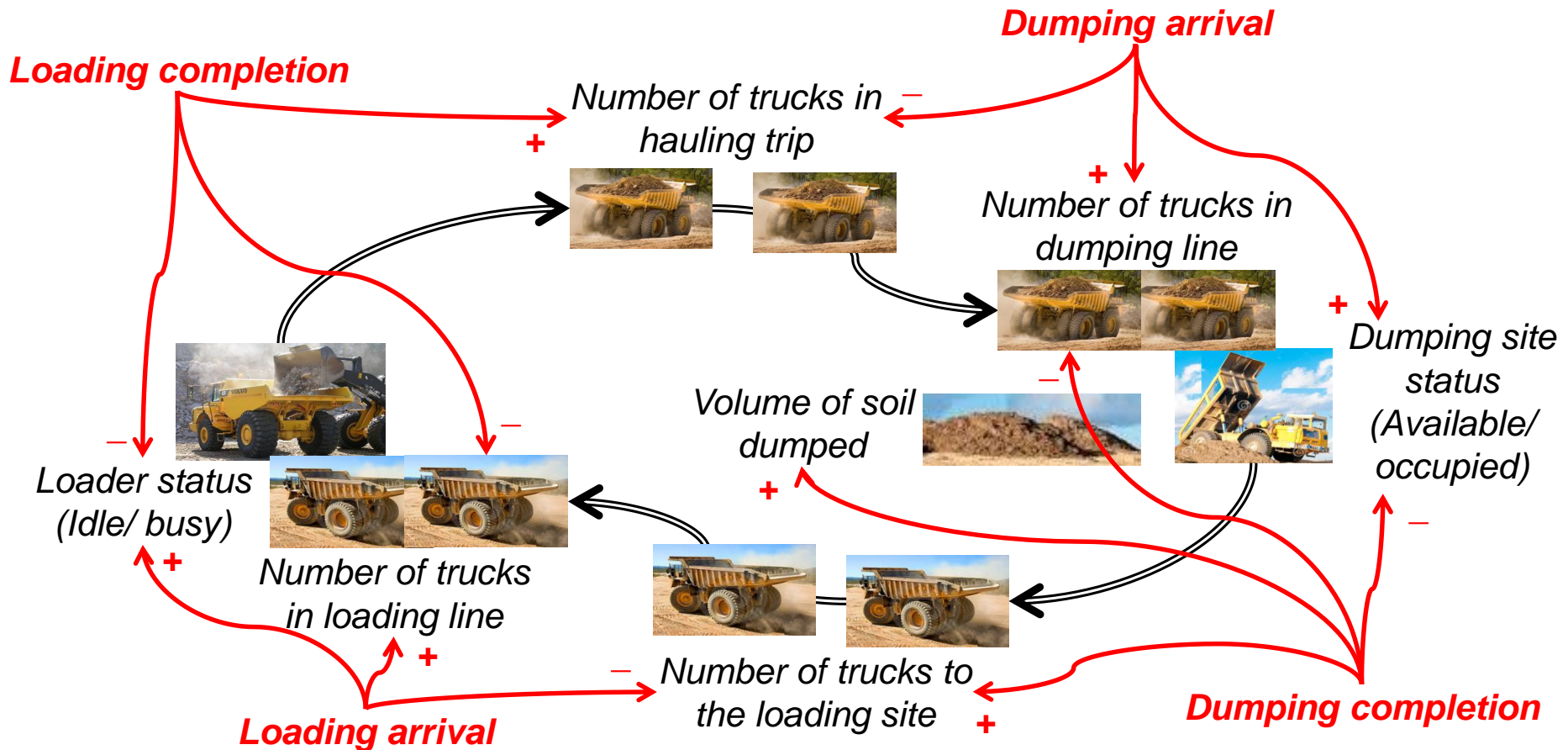
- We can usually remove events of the middle activity setups!



Updating system state

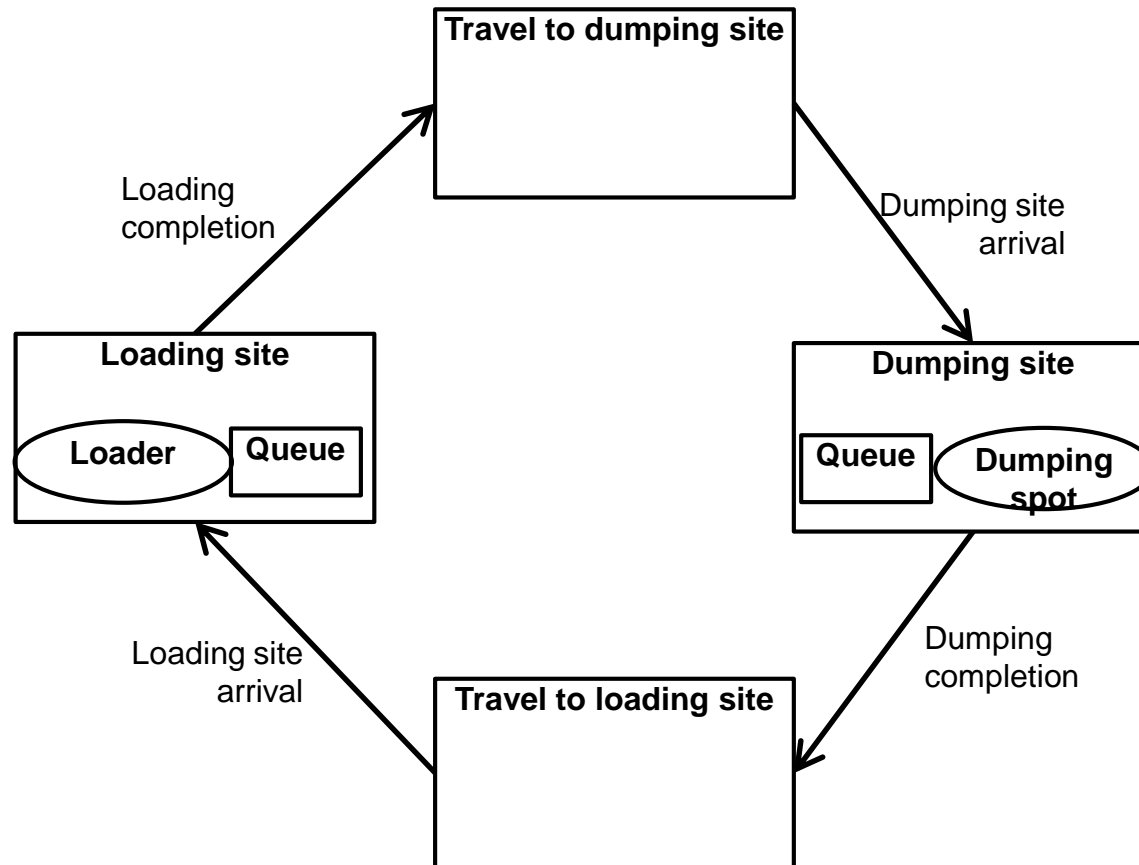
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- Example: Mutually exclusive set of events creating all system state updates with no overlap!




Updating system state

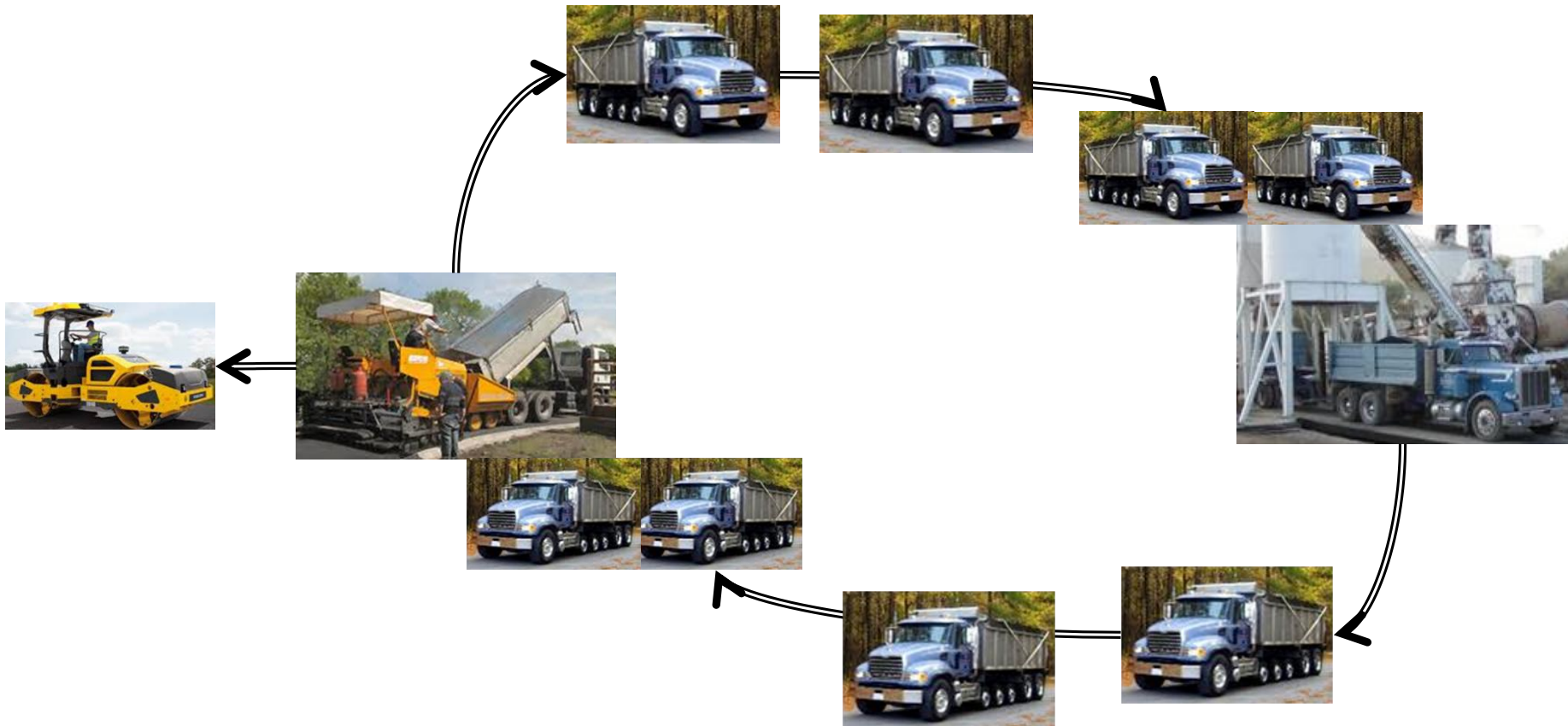
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Updating system state

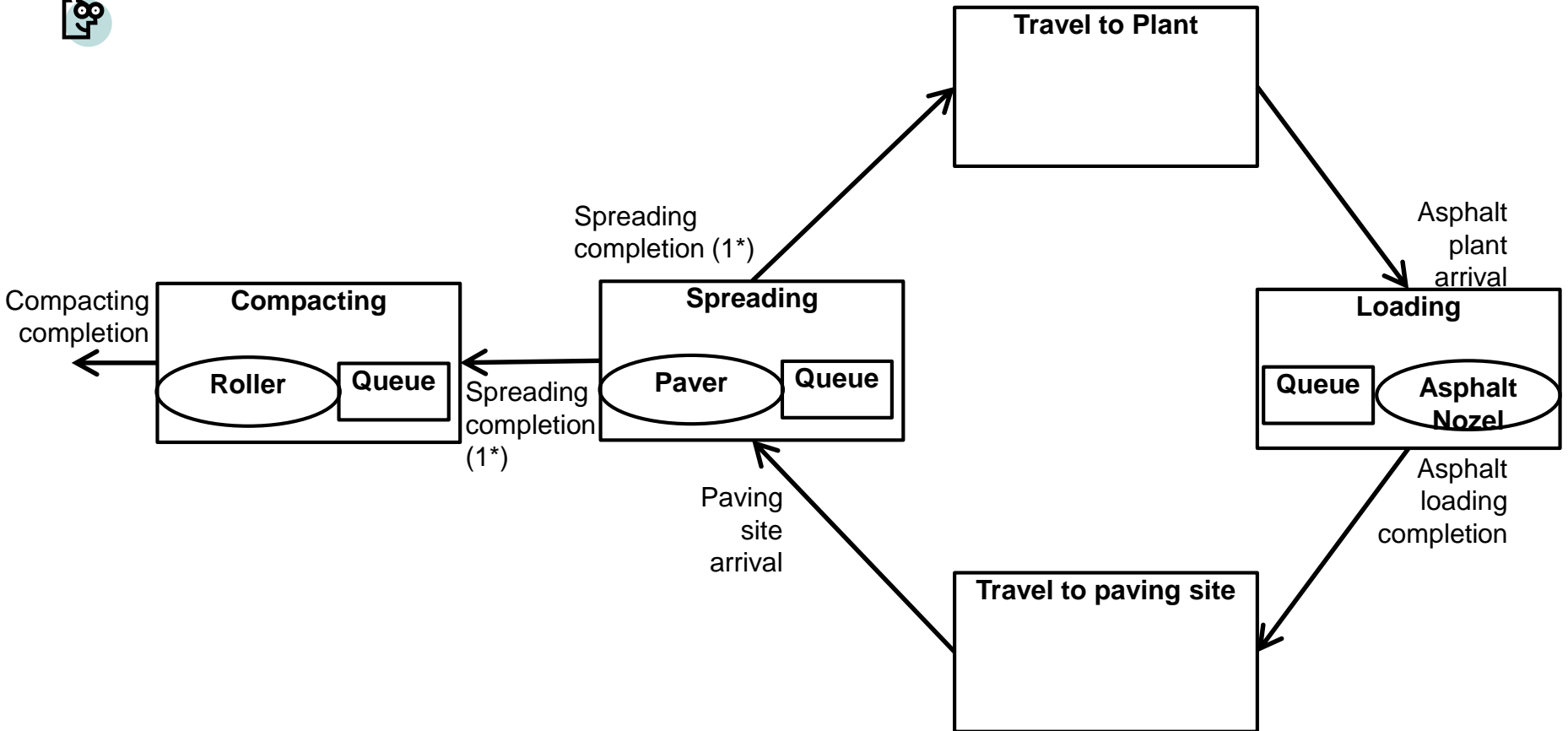
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 **In class practice 1:** In our paving operation example, determine mutually exclusive set of events and the way that they update state variables!



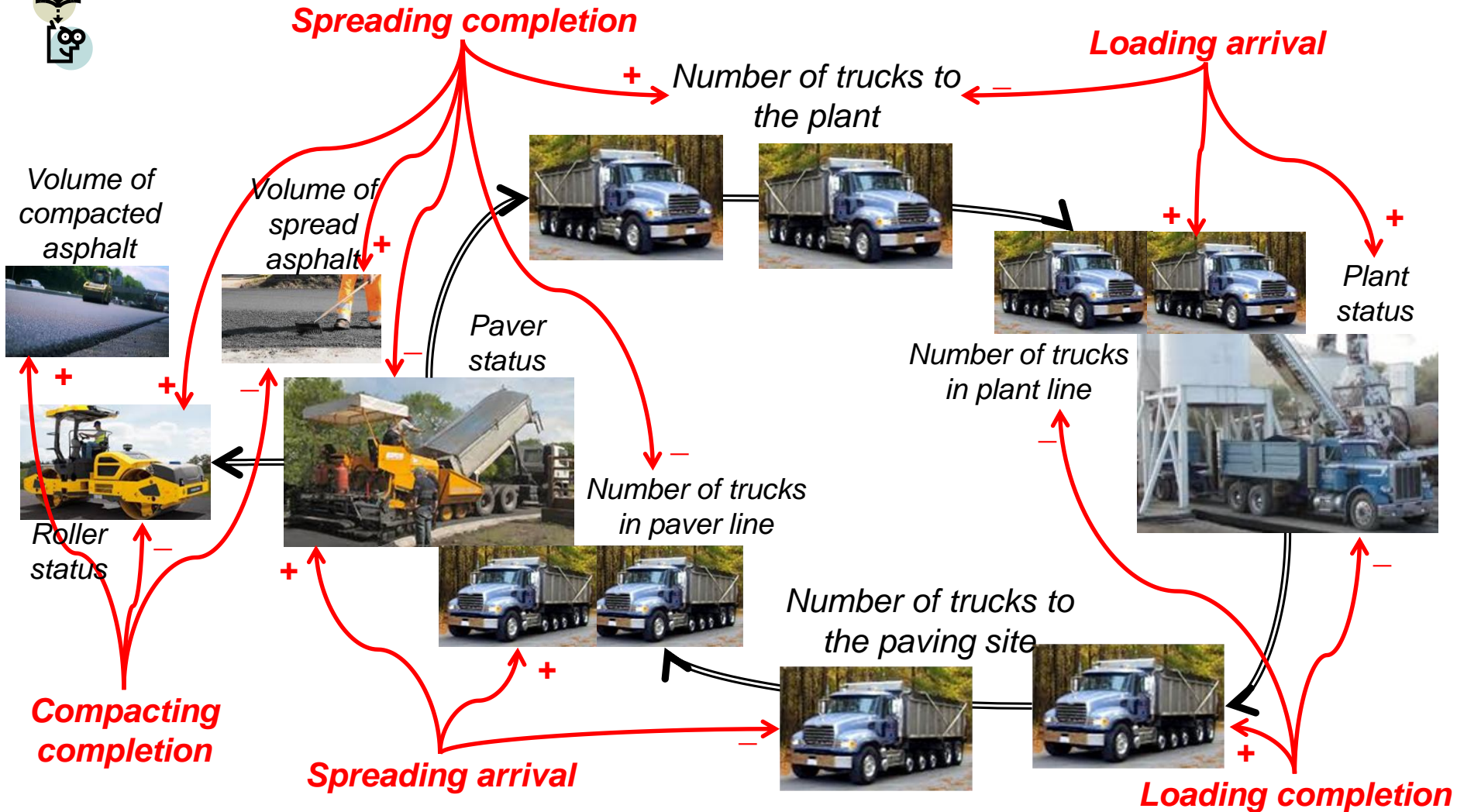
Updating system state

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Updating system state

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Simulation engine

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Tracking time in simulation systems:

Three different clocks:

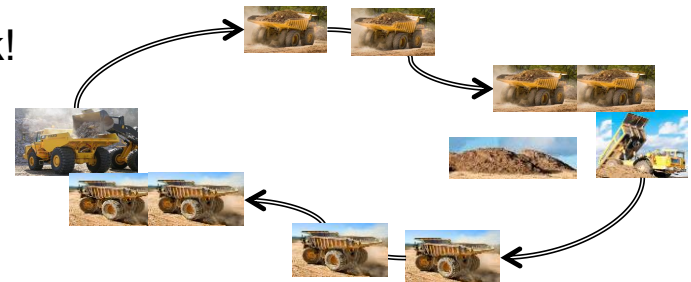
Wall clock: Represents our current time!



Computer calculation time: Represents time spent for doing calculations of the simulation model, it has the pace as wall clock, but starts from zero when a model calculation begins!



System clock: Represents time of being simulated system. It has completely different pace compared to the wall clock!

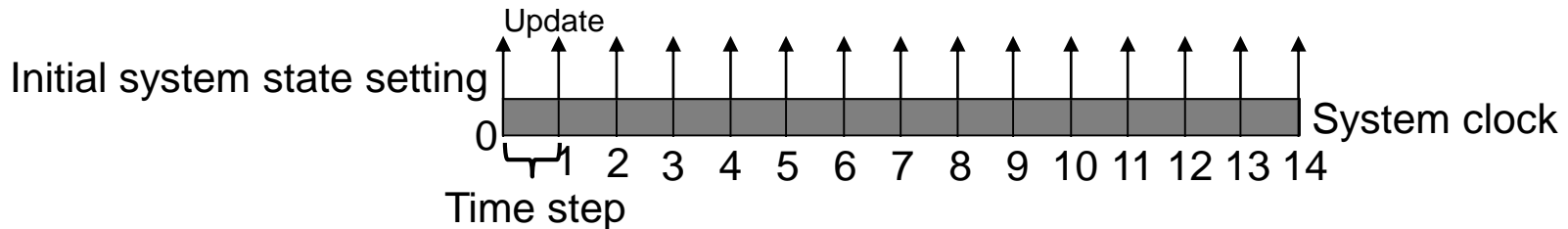


Simulation engine

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- Tracking time in simulation systems:

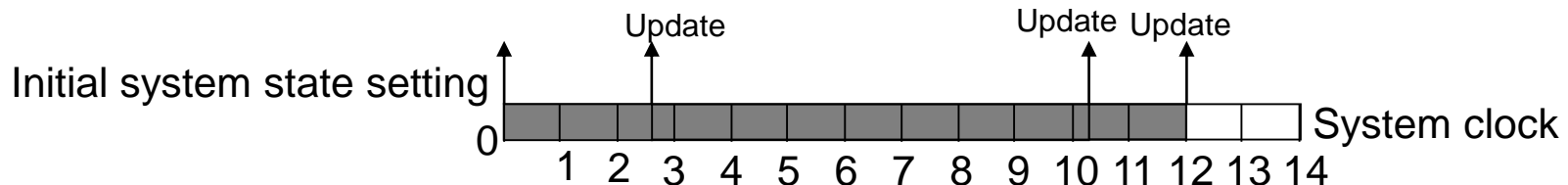
- Continuous simulation:



The smaller the time step, the more accurate the *calculation*!

For example depending on the system update pace and accuracy required, time step can be set at 1 second, 20 seconds, 1 minute, 50 minutes, 10 hours, 1 day, 1 month, 3 months, 1 year, etc.

- Discrete event simulation:

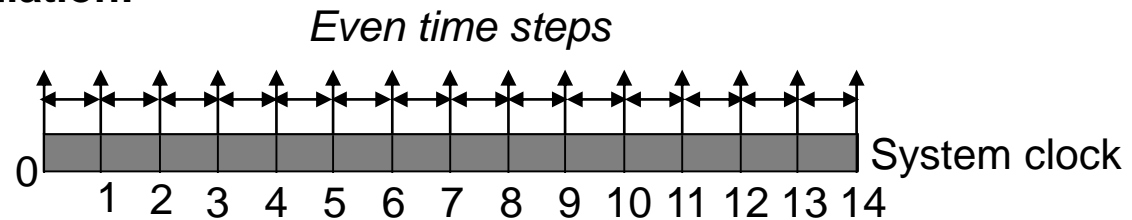


Simulation engine

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- Tracking time in simulation systems:

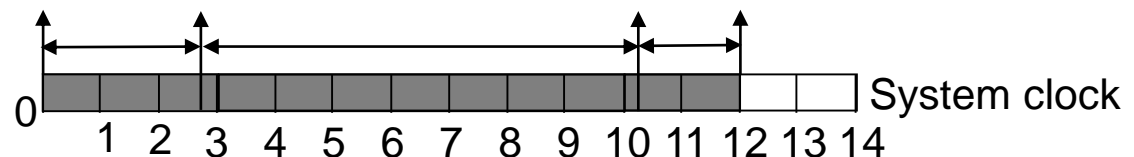
- Continuous simulation:



For tracing time in continuous simulation engines for each move we just need to advance time by one step and update system state base on equations relating different system components!

- Discrete event simulation:

Un-even time steps based on event occurrence



In what basis we can advance time in DES models?

Simulation engine

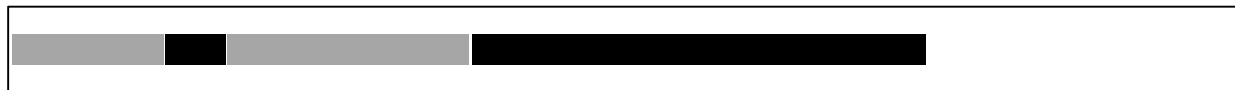
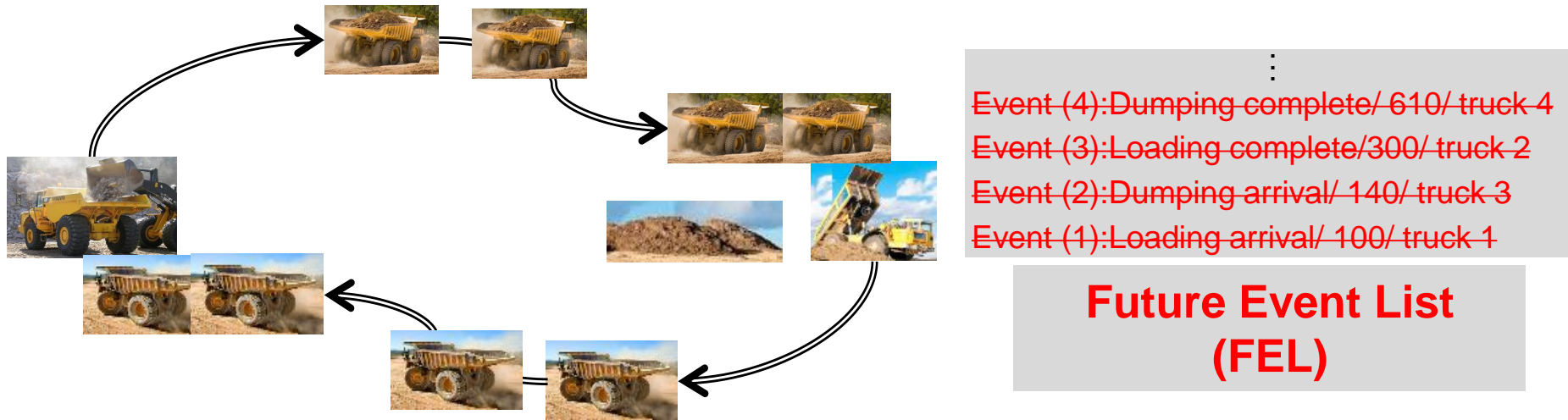
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- **Future event list (FEL):** For tracking time in DES engine we always maintain *minimum* number of future events identified for the system in a list called Future event list (FEL)!
- For every event on the list we maintain: type of event and time of occurrence. Depending on the type of information we need to collect in our simulation study we may also maintain information of *entity* (e.g., *entity id*) involved in the event!
- Identified events in FEL are maintained according their time of occurrence, we also call these events *scheduled* events. For advancing time we just need to withdraw first scheduled event from the list and move the time to its time of occurrence!

Simulation engine

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- Example: Time advancement in future event list:



Current Time: **610**



According to the specification you saw for FEL what computer programming feature you know for capturing FEL?

Simulation engine

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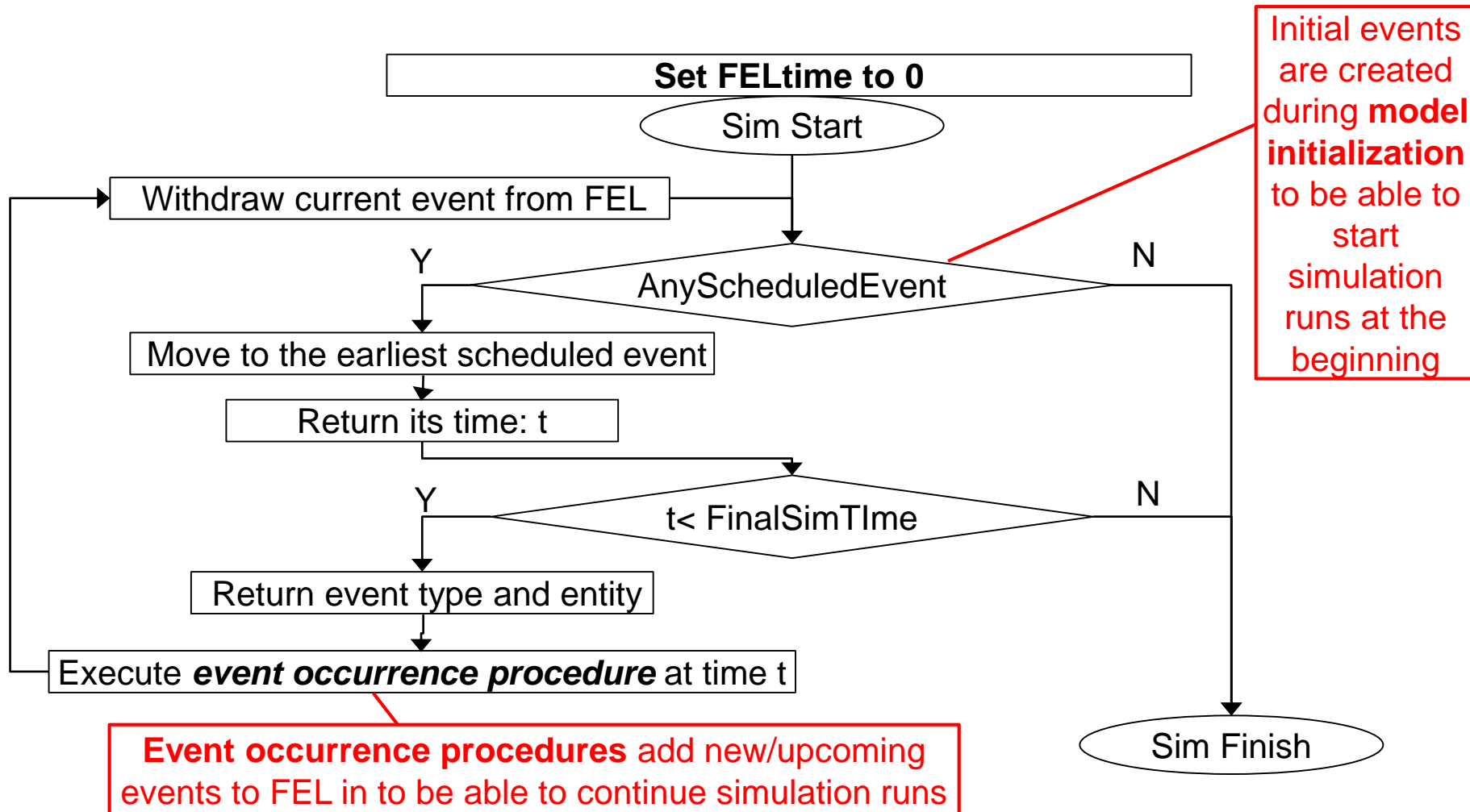
- **Future event list (FEL):**
 - FEL can properly be coded in computer programming as an *Array* variable!
 - Time advancing in simulation engine is our way for withdrawing (removing) scheduled events from FEL.
 - To be able to track the system updates during simulation study period we need to schedule new events (or add new upcoming events) to FEL over time!

 How can we identify all upcoming events and properly advance the time?

Simulation engine

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- Simulation engine procedure:



Model initialization


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- **Model initialization:** To be able to start simulating our simulation model we need to set model initialization through which time of the model is set to 0, initial system state is set up and initial system events are scheduled and added to FEL.
- **Example:** We are going to model our simple earthmoving example one working day from 7 am to 7 pm. There are two trucks, one loader and unlimited spots for dumping, working in project. Since we start from start of the working shift: there will be no trucks in the system; loader is idle. Truck1 arrives at loading site at time 7:00:30 and truck2 arrives at loading site at 7:01:05. We need to add these two arrival events to FEL to be able to start a simulation run!

Event (1):Loading arrival/ 7:01:05/ truck 2

Event (1):Loading arrival/ 7:00:30/ truck 1

Future Event List (FEL)

 **Initial condition:** After simulation begins, usually it takes some time for the model to pass initial condition, affected by *initial system state*. So, for simulation result analysis we usually need to let a simulation run continues until initial system state effect disappears!

Event occurrence procedure

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- **Event occurrence procedure** is our main tool for scheduling new/ upcoming events in our simulation model runs!

 *Remember:* System event is an *occurrence* that changes the state of the system.

- 1) For scheduling new events we need first to determine system state changes expected after occurrence of an event:

Example: *Truck arrives to the loading site;* changes made to the state variables by this event:

- 1) number of trucks on their way to the loading site is decreased by one
- 2) if there is an idle loader, number of busy loaders is increased by one (number of idle loaders is decreased by one)
- 3) if all loaders are busy, number of waiting trucks for loading is increased by one

 *Remember:* An activity is a period of time limited between two events where by occurrence of the first event, the occurrence of the second event will be known.

Event occurrence procedure

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- 2) If by occurrence of an event a new activity(s) is commenced, according to the definition of activity element, we can determine the finish event(s) of the activity(s). These events are new events which are scheduled and added to FEL!

Example 1: *Truck arrives to the loading site:*

- 1) number of trucks on their way to the loading site is decreased by one
- 2) if there is an idle loader, number of busy loaders is increased by one (number of idle loaders is decreased by one); **Schedule a new loading complete event and add it to FEL!**
- 3) if all loaders are busy, number of waiting trucks for loading is increased by one

Example 2: *Loading completion event:*

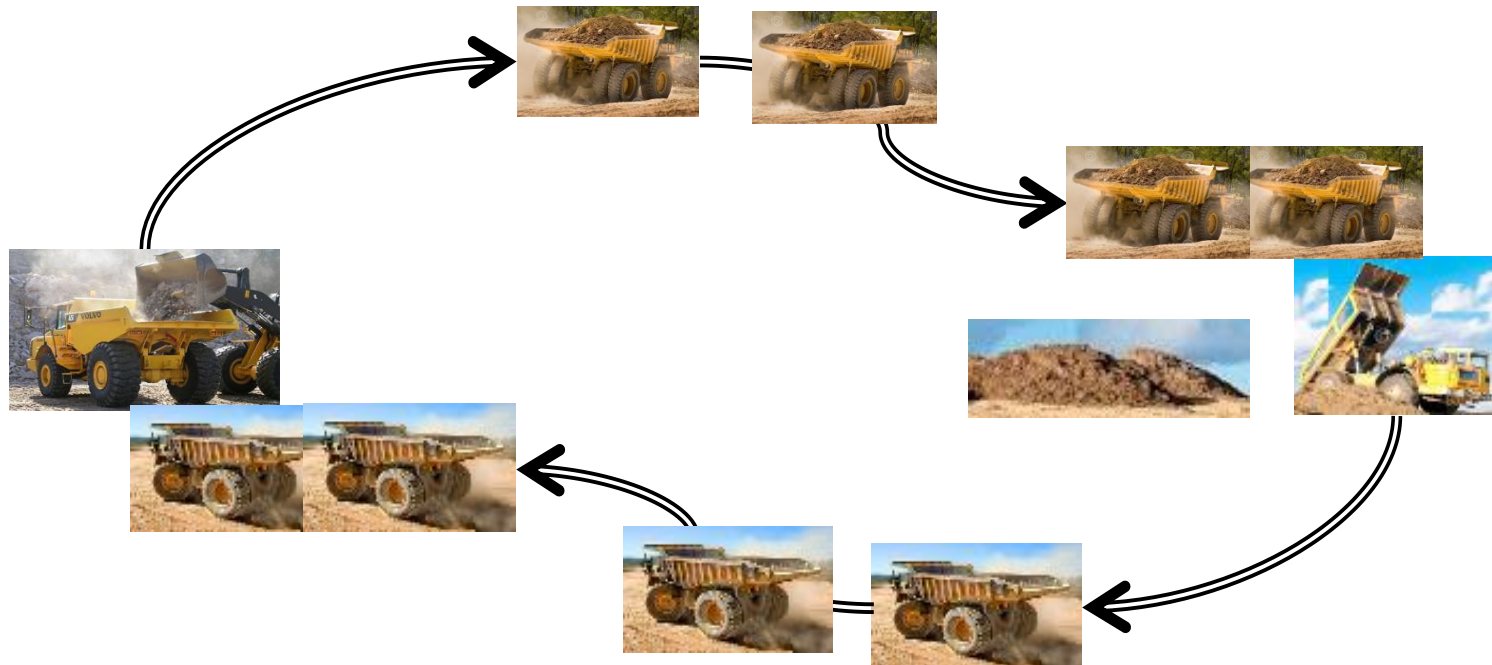
- 1) number of trucks on their way to dumping site is increased by one; **Schedule a new dumping arrival event and add it to FEL!**
- 2) if there is no truck waiting to be loaded, number of idle loaders is increased by one
- 3) if there are trucks waiting to be loaded, number of trucks waiting to be loaded is decreased by one; **Schedule a new loading completion event and add it to FEL!**

Event occurrence procedure

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In class practice 2: Two events among set of mutually exclusive events identified in our earth moving example are Truck arrives to the dumping site and Dumping completion event, what are expected system updates by these events occurrences? What are new events scheduled (added to FEL) as results of these events occurrences?



Event occurrence procedure

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Truck arrives to the dumping site:

- 1) number of trucks on their way to the dumping site is decreased by one
- 2) if there is enough room for the truck to start dumping, available rooms in the dumping area is decreased by one; **Schedule a new dumping complete event and add it to FEL!**
- 3) if all dumping lots are occupied, number of waiting trucks for dumping is increased by one

Dumping completion event:

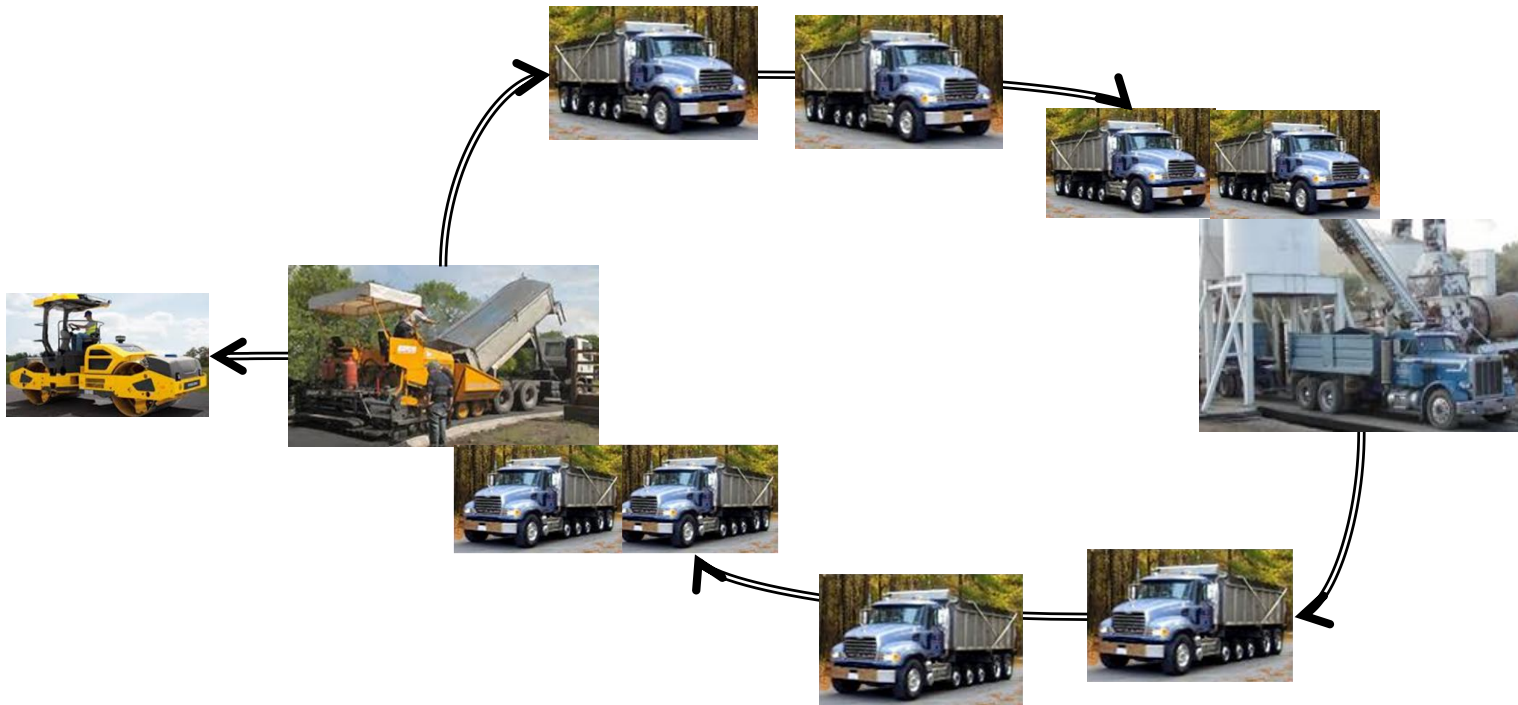
- 1) number of trucks on their way to loading site is increased by one; **Schedule a new loading arrival event and add it to FEL!**
- 2) if there is no truck waiting for dumping, number of idle dumping spots is increased by one
- 3) if there are trucks waiting for dumping, number of trucks waiting for dumping is decreased by one; **Schedule a new dumping completion event and add it to FEL!**

Event occurrence procedure

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In class practice 3: Two events among set of mutually exclusive events identified in our road paving example are Spreading completion and Compacting completion, what are expected system updates by these events occurrences? What are new events scheduled (added to FEL) as results of these events occurrences?



Event occurrence procedure

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Spreading completion:

- 1) number of trucks on their way to the plant is increased by one; **Schedule a new plant arrival event and add it to FEL!**
- 2) if there is no truck waiting for spreading, number of idle pavers is increased by one
- 3) if there are trucks waiting for spreading, number of trucks waiting for spreading is decreased by one; **Schedule a new spreading completion event and add it to FEL!**
- 4) If there is no idle roller, increase spread asphalt-batch volume
- 5) If there are idle rollers, decrease number of idle rollers by one; **Schedule a new asphalt-batch compacting completion event and add it to FEL!**

Compacting completion:

- 1) Increase volume of compacted asphalt-batch
- 2) If there is no spread asphalt-batch remained uncompacted, increase number of idle rollers
- 3) If there is spread asphalt-batch(es) (uncompacted), decrease number of spread asphalt-batch; **Schedule a new asphalt-batch compacting completion event and add it to FEL!**

Event occurrence procedure

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- **Event occurrence procedure in flowchart:** Event occurrence procedures are important parts of simulation programs. To be able to implement them, by programming and through coding, more properly (specially for more complicated event occurrence procedures), it is suggested that we develop flowcharts for them!

Example: For “*Truck arrives to the loading site*” and “*Loading completion*” events we will have written procedure and procedure in flowchart as:

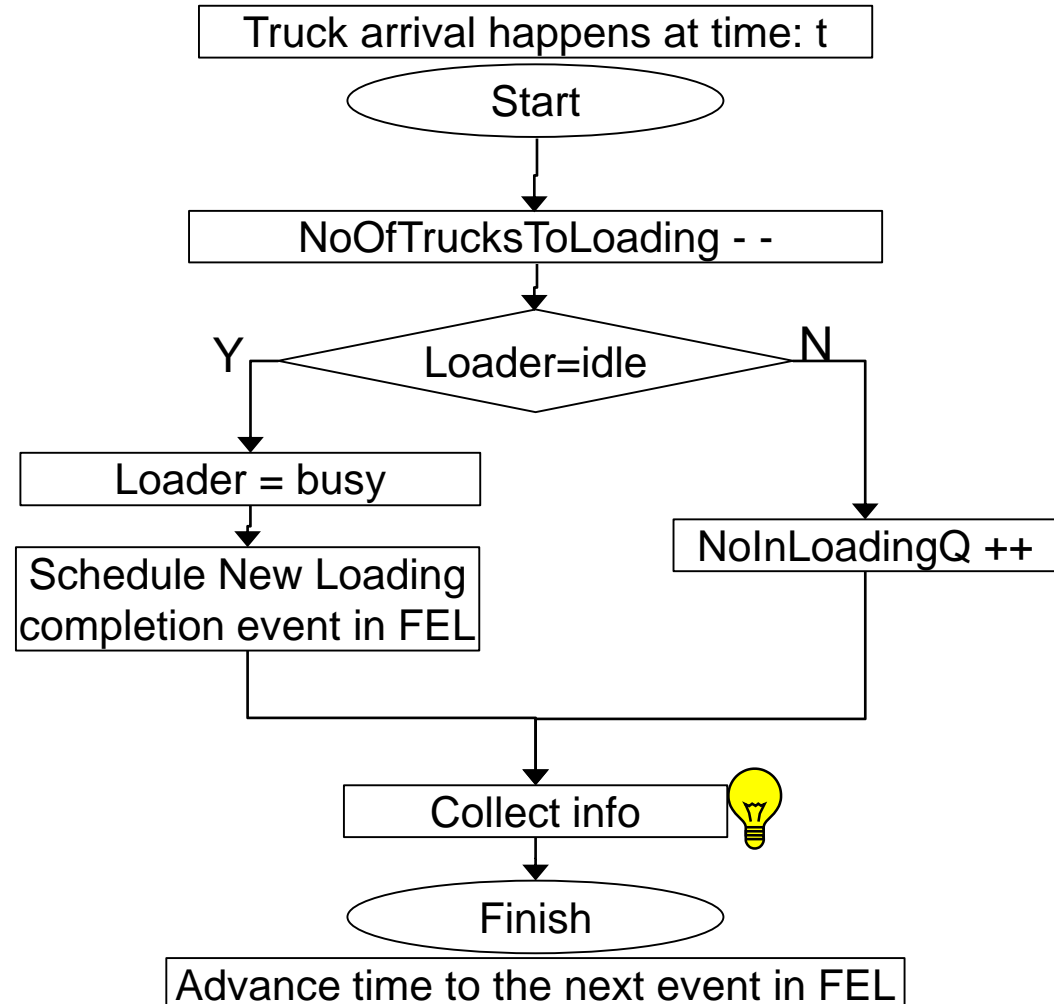
Event occurrence procedure

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1) number of trucks on their way to the loading site is decreased by one

2) if there is an idle loader, number of busy loaders is increased by one (number of idle loaders is decreased by one); **Schedule a new loading complete event and add it to FEL!**

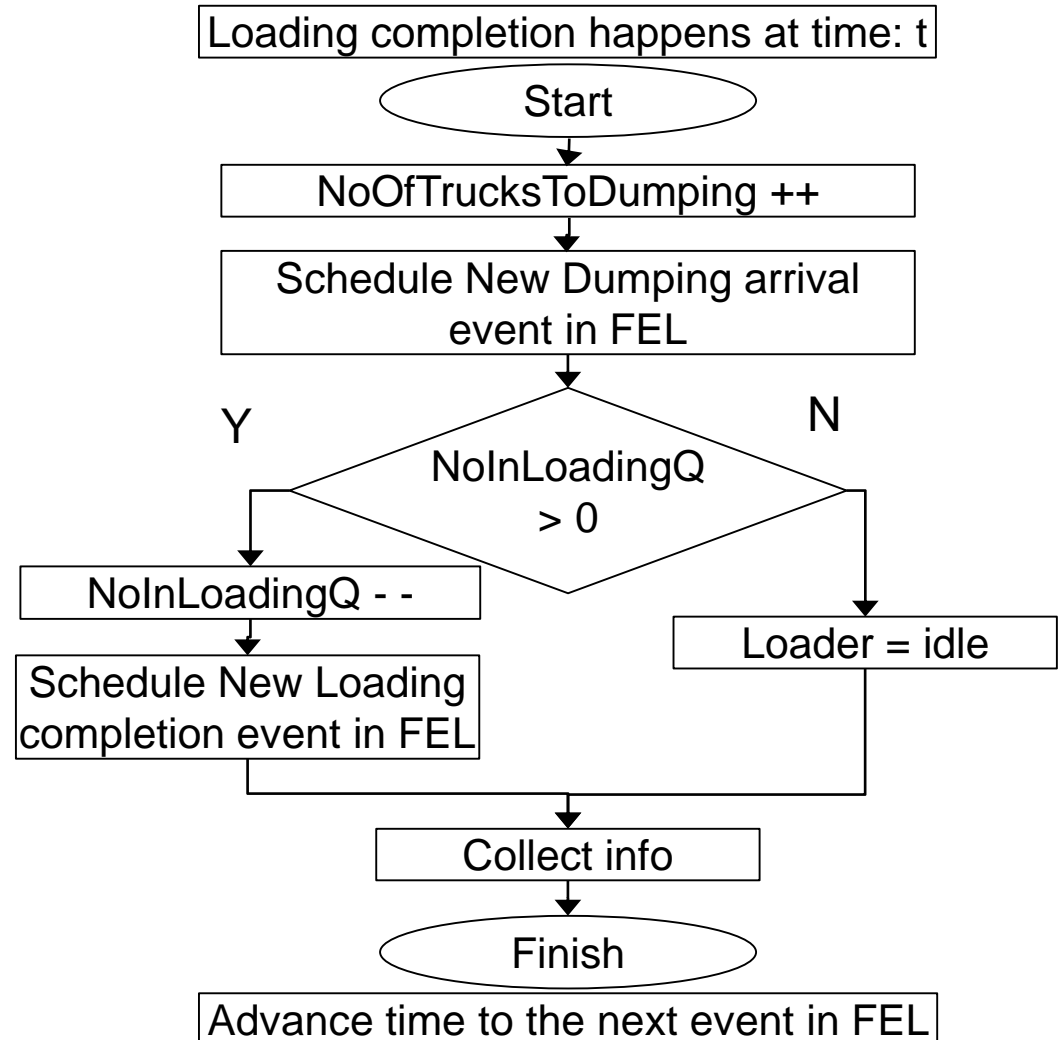
3) if all loaders are busy, number of waiting trucks for loading is increased by one



Event occurrence procedure

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- 1) number of trucks on their way to dumping site is increased by one;
Schedule a new dumping arrival event and add it to FEL!
- 2) if there is no truck waiting to be loaded, number of idle loaders is increased by one
- 3) if there are trucks waiting to be loaded, number of trucks waiting to be loaded is decreased by one;
Schedule a new loading completion event and add it to FEL!

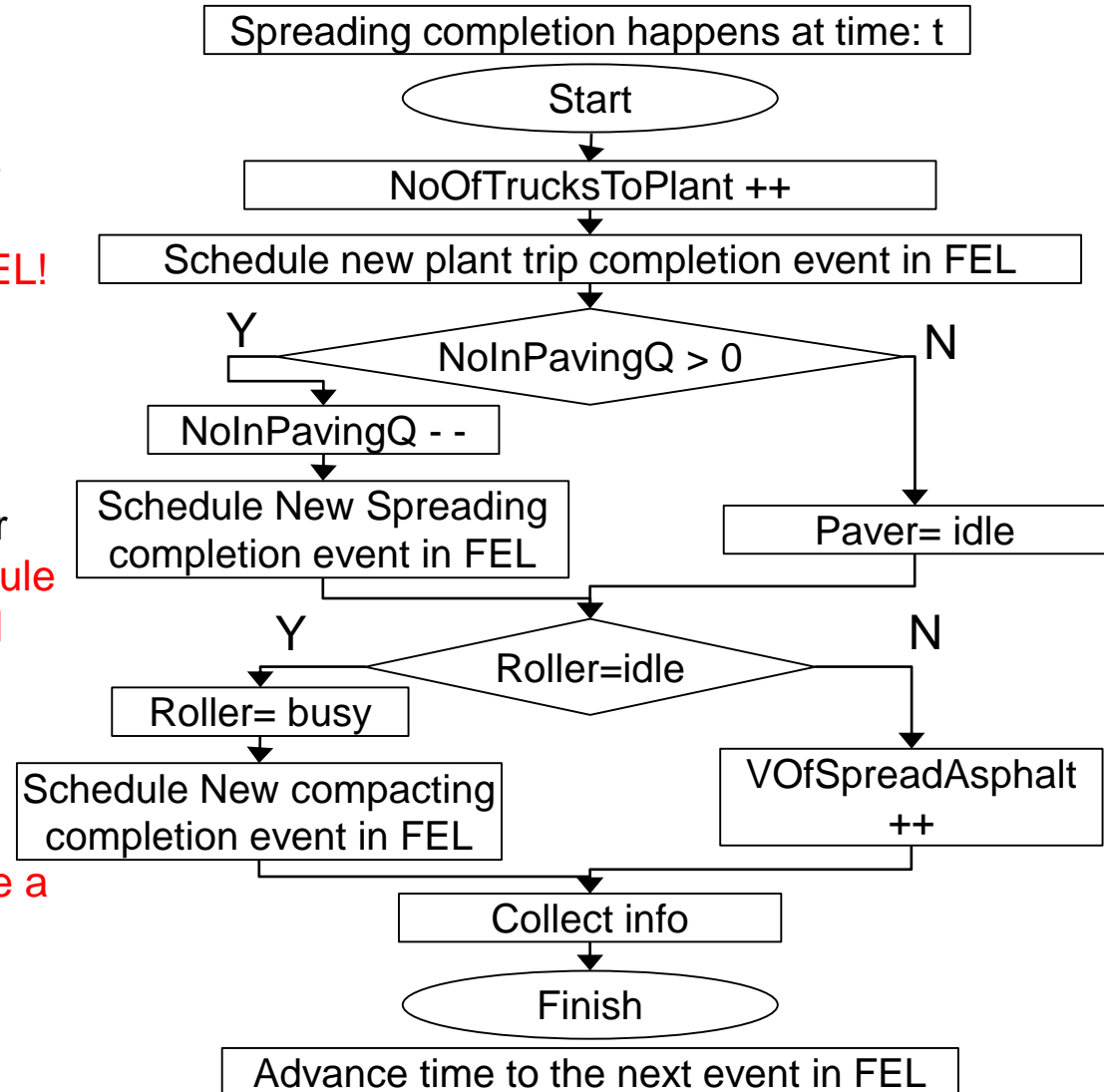


Event occurrence procedure

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- 1) number of trucks on their way to the plant is increased by one; **Schedule a new plant arrival event and add it to FEL!**
- 2) if there is no truck waiting for spreading, number of idle pavers is increased by one
- 3) if there are trucks waiting for spreading, number of trucks waiting for spreading is decreased by one; **Schedule a new spreading completion event and add it to FEL!**
- 4) If there is no idle roller, increase spread asphalt-batch volume
- 5) If there are idle rollers, decrease number of idle rollers by one; **Schedule a new asphalt-batch compacting completion event and add it to FEL!**

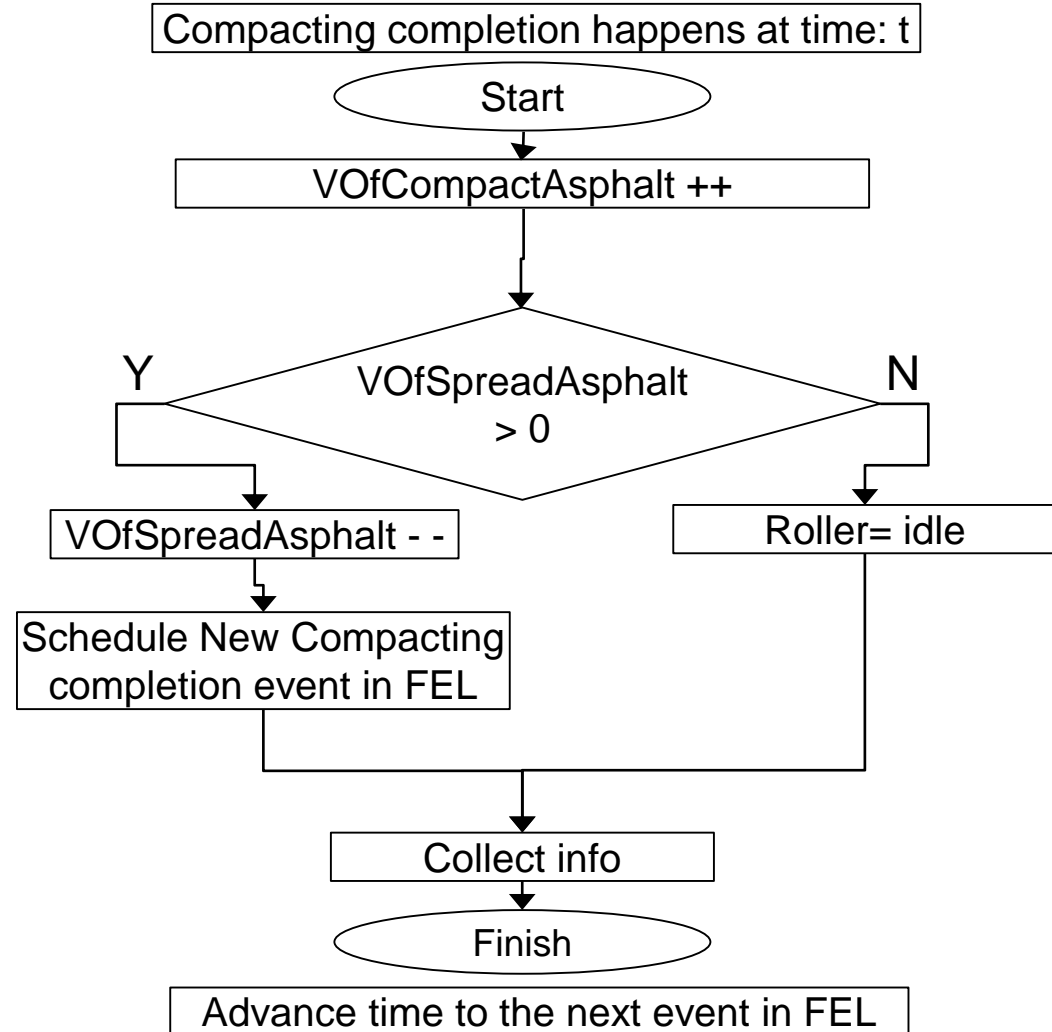


Event occurrence procedure

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- 1) Increase volume of compacted asphalt-batch
- 2) If there is no spread asphalt-batch remained uncompact, increase number of idle rollers
- 3) If there is spread asphalt-batch(s) (uncompact), decrease number of spread asphalt-batch; **Schedule a new asphalt-batch compacting completion event and add it to FEL!**



Hand simulation

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- To better understand steps taken in computer simulation, in hand simulation we are going to follow similar steps a computer simulation program follows, though with hand and on paper!
- For doing hand simulation we need:
 - 1) Recognize model elements
 - 2) Determine event procedures
 - 3) Initialize the model
 - 4) Start simulation engine procedure; start advancing time and executing related event occurrence procedure

Remember to update system state after each event occurrence

Hand simulation

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- **Example:** Suppose our earthmoving example with 3 trucks and 1 loader in the system. There is no limitation in number of dumping sites. At this stage we are going to hand-simulate a *deterministic* model where all activity durations are determined:
 - Loading: 10 minutes
 - Trip to dumping site: 5 minutes
 - Dumping 2 minutes
 - Trip from dumping: 5 minutes

Hand simulation:

1- Model elements:

Entity: Truck


Resource: Loader

Hand simulation

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□ Example (cont'd):

Activity:

Since there is no limitations in dumping area, we are not going to see any line or waiting time in the dumping area, we can easily reduce number of activities to 2 (why?): 

- Loading: 10 minutes
- Trip: 12 minutes

Event:

Loading site arrival; Loading completion

System state:

Num of trucks in loading Queue; Loader status; Num of trucks on trip(can be calculated from other two state variable after *initial condition* passed so we do not track its changes!)

Hand simulation

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□ Example (cont'd):

2- Determine event procedures

Truck arrives to the loading site:

- 1) number of trucks on trip is decreased by one
- 2) If loader is idle, make loader busy; **Schedule a new loading complete event!**
- 3) If loader is busy, number of waiting trucks for loading is increased by one

Loading completion event:

- 1) number of trucks on trip is increased by one; **Schedule a new loading arrival event!**
- 2) if there is no truck waiting to be loaded, make loader idle
- 3) if there are trucks waiting to be loaded, number of trucks waiting to be loaded is decreased by one; **Schedule a new loading completion event and add it to FEL!**

Hand simulation

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□ Example (cont'd):

3- Initialize the model

State variables: Num of trucks in loading Queue = 0; Loader status=idle

Events: Truck1 arrives at 6:59:01; Truck2 arrives at 6:59:52; Truck3 arrives at 7:19:30

System state			
Time	Event	Queue	Loader status
0		0	0

FEL		
Time	Event	Truck
6:59:01	Initial Arrival	1
6:59:52	Initial Arrival	2
7:19:30	Initial Arrival	3

Hand simulation

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□ Example (cont'd):

4- Start simulation engine procedure

Event 1: 6:59:01/ Arrival/ Truck1

System state			
Time	Event	Queue	Loader status
0		0	0
6:59:01	Initial Arriva	0	1

It is recommended to have FEL array indexed / sorted by event time and placing new events in FEL in order!



FEL		
Time	Event	Truck
6:59:01	Initial Arrival	1
6:59:52	Initial Arrival	2
7:09:01	Completion	1
7:19:30	Initial Arrival	3

Hand simulation

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□ **Example (cont'd):**

Event 2: 6:59:52/ Arrival/ Truck2

System state			
Time	Event	Queue	Loader status
0		0	0
6:59:01	Initial Arriva	0	1
6:59:52	Initial Arriva	1	1

FEL		
Time	Event	Truck
6:59:01	Arrival	1
6:59:52	Arrival	2
7:09:01	Completion	1
7:19:30	Arrival	3

Event 3: 7:09:01/ Completion/ Truck1

System state			
Time	Event	Queue	Loader status
0		0	0
6:59:01	Initial Arriva	0	1
6:59:52	Initial Arriva	1	1
7:09:01	Completion	0	1

FEL		
Time	Event	Truck
7:09:01	Completion	1
7:19:01	Completion	2
7:19:30	Initial Arrival	3
7:21:01	Arrival	1



Hand simulation

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□ **Example (cont'd):**

Event 4: 7:19:01/ Completion/ Truck2

System state			
Time	Event	Queue	Loader status
0		0	0
6:59:01	Initial Arriva	0	1
6:59:52	Initial Arriva	1	1
7:09:01	Completion	0	1
7:19:01	Completion	0	0



FEL		
Time	Event	Truck
7:19:01	Completion	2
7:19:30	Initial Arrival	3
7:21:01	Arrival	1
7:31:01	Arrival	2

Event 5: 7:19:30/ arrival/ Truck3

System state			
Time	Event	Queue	Loader status
0		0	0
6:59:01	Initial Arriva	0	1
6:59:52	Initial Arriva	1	1
7:09:01	Completion	0	1
7:19:01	Completion	0	0
7:19:30	Arrival	0	1

FEL		
Time	Event	Truck
7:19:30	Initial Arrival	3
7:21:01	Arrival	1
7:29:30	Completion	3
7:31:01	Arrival	2

Hand simulation

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□ Example (cont'd):

System state			
Time	Event	Queue	Loader status
0		0	0
6:59:01	Arrival	0	1
6:59:52	Arrival	1	1
7:09:01	Completion	0	1
7:19:01	Completion	0	0
7:19:30	Arrival	0	1
7:21:01	Arrival	1	1
7:29:30	Completion	0	1
7:31:01	Arrival	1	1
7:39:30	Completion	0	1
7:41:30	Arrival	1	1
7:49:30	Completion	0	1

FEL		
Time	Event	Truck
7:19:30	Arrival	3
7:21:01	Arrival	4
7:29:30	Completion	3
7:31:01	Arrival	2
7:39:30	Completion	4
7:41:30	Arrival	3
7:49:30	Completion	2
7:51:30	Arrival	1
7:59:30	Completion	3
8:01:30	Arrival	2

Hand simulation

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□ Example (cont'd):



Questions to be answered by gathering simulation data?

- What is average productivity (dumping per hour)?
- What is the maximum queue size?
- What is the average waiting time?
- What is idle-time percentage of the loader?

Hand simulation

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□ **Example (cont'd):**

Questions to be answered by gathering simulation data?

- What is average productivity (dumping per hour)?

System state			
Time	Event	Queue	Loader status
0		0	0
6:59:01	Initial Arrival	0	1
6:59:52	Initial Arrival	1	1
7:09:01	Completion	0	1
7:19:01	Completion	0	0
7:19:30	Initial Arrival	0	1
7:21:01	Arrival	1	1
7:29:30	Completion	0	1
7:31:01	Arrival	1	1
7:39:30	Completion	0	1
7:41:30	Arrival	1	1
7:49:30	Completion	0	1

Average productivity

Total 3 dumping trips completion in (7:49:30 - 6:59:01 => 50' 29" or 3 in 0.843h or rate of **3.56/h** dumping trip completion.

Is this accurate?

Hand simulation

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- **Example (cont'd):**

Questions to be answered by gathering simulation data?

- What is the maximum queue size? 1

Hand simulation

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□ **Example (cont'd):**

Questions to be answered by gathering simulation data?

- What is the average waiting time?

System state					
Time	Event	Queue	Loader status		Waiting time
0		0	0		
6:59:01	Initial Arrival	0	1	Truck 1 in/out	0
6:59:52	Initial Arrival	1	1	Truck 2 in	
7:09:01	Completion	0	1	Truck 2 out	0:09:09
7:19:01	Completion	0	0		
7:19:30	Initial Arrival	0	1	Truck 3 in/out	0
7:21:01	Arrival	1	1	Truck 1 in	
7:29:30	Completion	0	1	Truck 1 out	0:08:29
7:31:01	Arrival	1	1	Truck 2 in	
7:39:30	Completion	0	1	Truck 2 out	0:08:29
7:41:30	Arrival	1	1	Truck 3 in	
7:49:30	Completion	0	1	Truck 3 out	0:08:00
				Average:	0:05:41

Is this accurate?

Hand simulation

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□ **Example (cont'd):**

Questions to be answered by gathering simulation data?

- What is idle-time percentage of the loader?

System state					
Time	Event	Queue	Loader status		Loader idle time
0		0	0		
6:59:01	Initial Arrival	0	1		
6:59:52	Initial Arrival	1	1		
7:09:01	Completion	0	1		
7:19:01	Completion	0	0	Idle start	
7:19:30	Initial Arrival	0	1	Idle finish	0:00:29
7:21:01	Arrival	1	1		
7:29:30	Completion	0	1		
7:31:01	Arrival	1	1		
7:39:30	Completion	0	1		
7:41:30	Arrival	1	1		
7:49:30	Completion	0	1		
Total time		0:50:29	Total idle time		0:00:29
			Idle percentage		0.96%

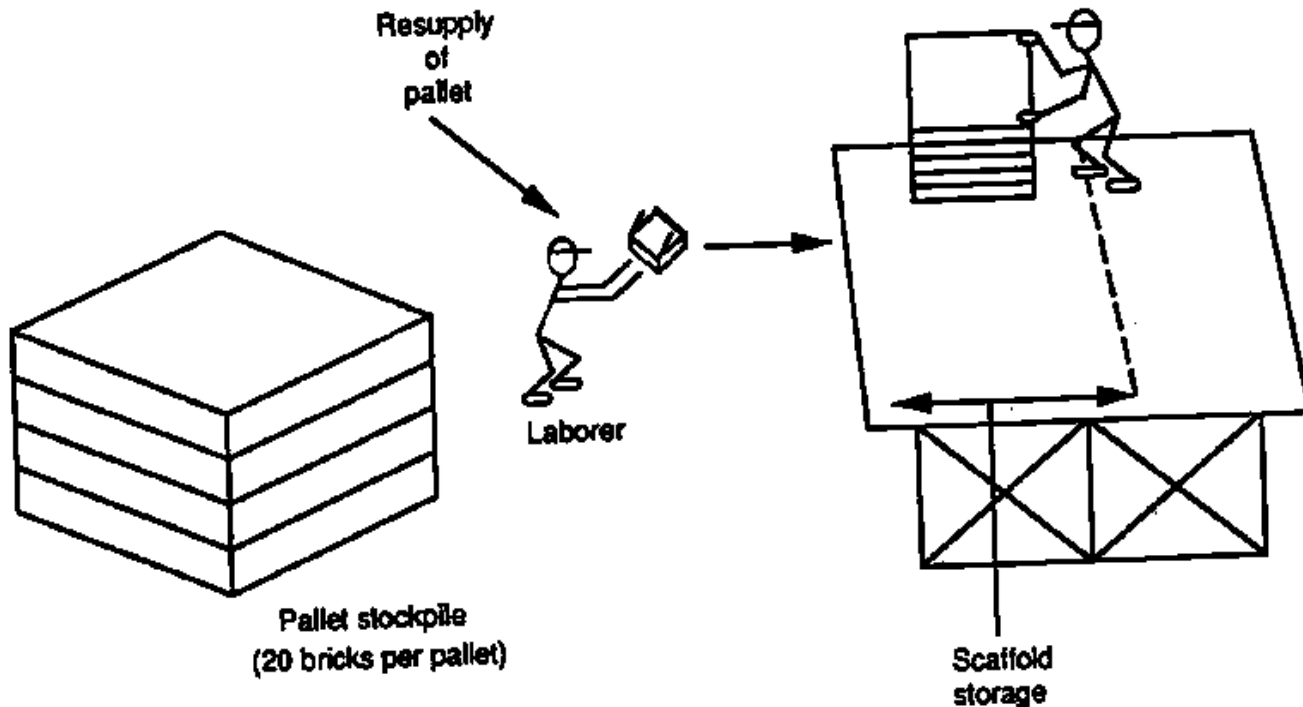
Is this accurate?

Home assignment 3

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Consider a mason-laborer problem in which the laborer stockpiles brick pallets on a scaffold. The scaffold is configured to allow for the stacking of two 30-brick pallets. There is one laborer who serves three masons. A schematic diagram showing the sequence of the operation is presented below.



Home assignment 3

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- A time study was carried out to obtain the durations required for the supply of packets and laying of bricks (each pallet-30 bricks).
 - Duration for the laborer to stockpile one brick pallets on a scaffold: 5 minutes
 - Duration for a mason to place one brick pallets: 13 minutes
- Assume that there is an infinite supply of brick pallets and there are no bricks stacked on the scaffold at the beginning of the operation. Work starts at 7 am and finishes 7 pm.
Hand simulate the model for 1 hours!
- *How long labor is idle? How long masons (in total) are idle?*

Due in 2 weeks



Thank you!