Digital Twins for Simulation & Optimisation of Heavy Equipment Multipart Logistics (HEML)

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Value creation through incremental innovation

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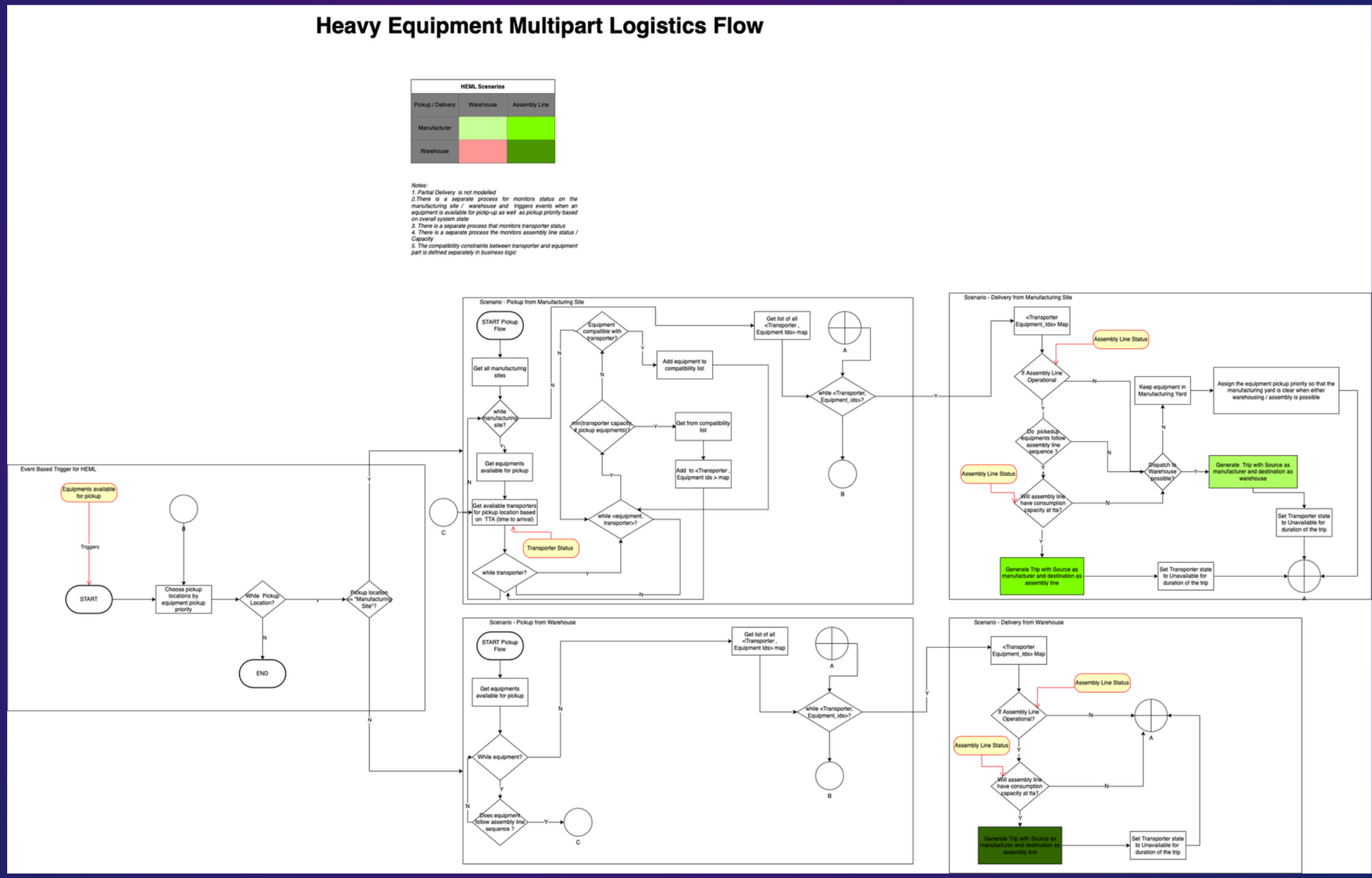
WHY IS IT RELEVANT?

WHAT IS HEML?


Heavy Equipment Multipart Logistics Flow
HEML Scenarios
Pickup / Delivery
Warehouse
Assembly Line
Manufacturer
Warehouse
Notes:
1. Partial Delivery is not modelled
2.There is a separate process for monitors status on the manufacturing site / warehouse and triggers events when an equipment is available for pickup as well as pickup priority based on overall system state
3. There is a separate process that monitors transporter status
4. There is a separate process the monitors assembly line status / Capacity
5. The compatibility constraints between transporter and equipment part is defined separately in business logic
Event Based Trigger for HEML
Equipments available for pickup
Triggers
START
Choose pickup locations by equipment pickup priority
While Pickup Location?
END
Pickup location is "Manufacturing Site"?
Scenario - Pickup from Manufacturing Site
START Pickup Flow
Get all manufacturing sites
while manufacturing site?
Get equipments available for pickup
Get available transporters for pickup location based on TTA (time to arrival)
Transporter Status
while transporter?
Equipment compatible with transporter?
Add equipment to compatibility list
Get list of all <Transporter , Equipment Ids> map
while <Transporter, Equipment_Ids>?
min(transporter capacity, # pickup equipments)?
Get from compatibility list
Add to <Transporter , Equipment ids > map
while <equipment, transporter>?
Scenario - Delivery from Manufacturing Site
<Transporter Equipment_Ids> Map
Assembly Line Status
If Assembly Line Operational
Keep equipment in Manufacturing Yard
Assign the equipment pickup priority so that the manufacturing yard is clear when either warehousing / assembly is possible
Do pickedup equipments follow assembly line sequence ?
Dispatch to Warehouse possible?
Generate Trip with Source as manufacturer and destination as warehouse
Assembly Line Status
Will assembly line have consumption capacity at tta?
Generate Trip with Source as manufacturer and destination as assembly line
Set Transporter state to Unavailable for duration of the trip
Set Transporter state to Unavailable for duration of the trip
Scenario - Pickup from Warehouse
START Pickup Flow
Get equipments available for pickup
While equipment?
Does equipment follow assembly line sequence ?
Get list of all <Transporter , Equipment Ids> map
while <Transporter, Equipment_Ids>?
Scenario - Delivery from Warehouse
<Transporter Equipment_Ids> Map
Assembly Line Status
If Assembly Line Operational?
Assembly Line Status
Will assembly line have consumption capacity at tta?
Generate Trip with Source as manufacturer and destination as assembly line
Set Transporter state to Unavailable for duration of the trip

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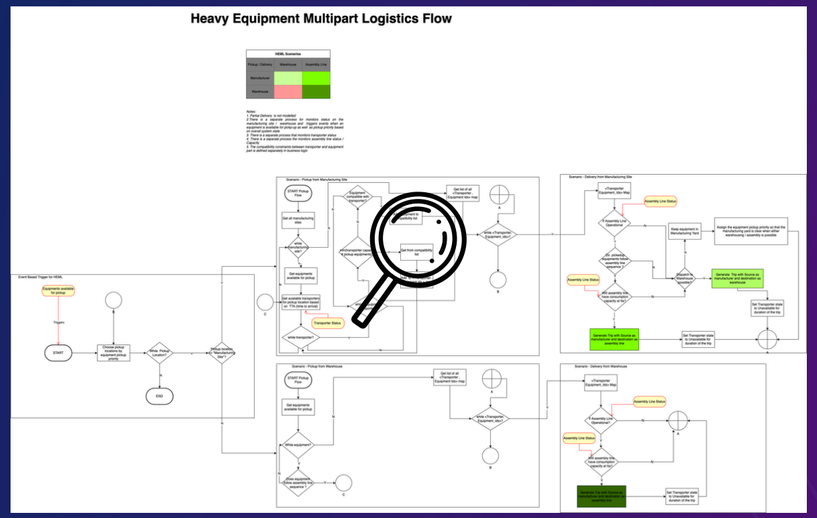
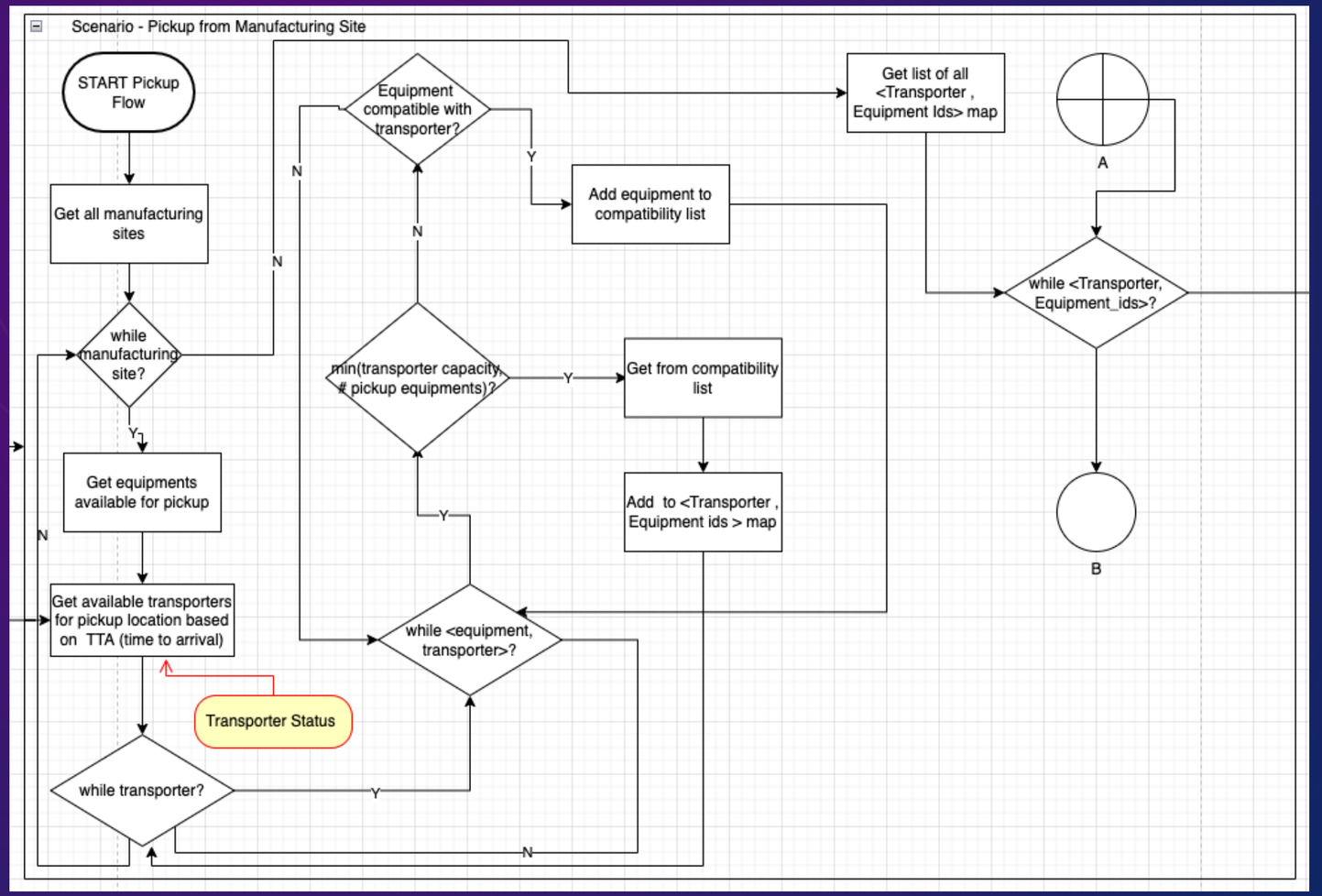


Scenario - Pickup from Manufacturing Site



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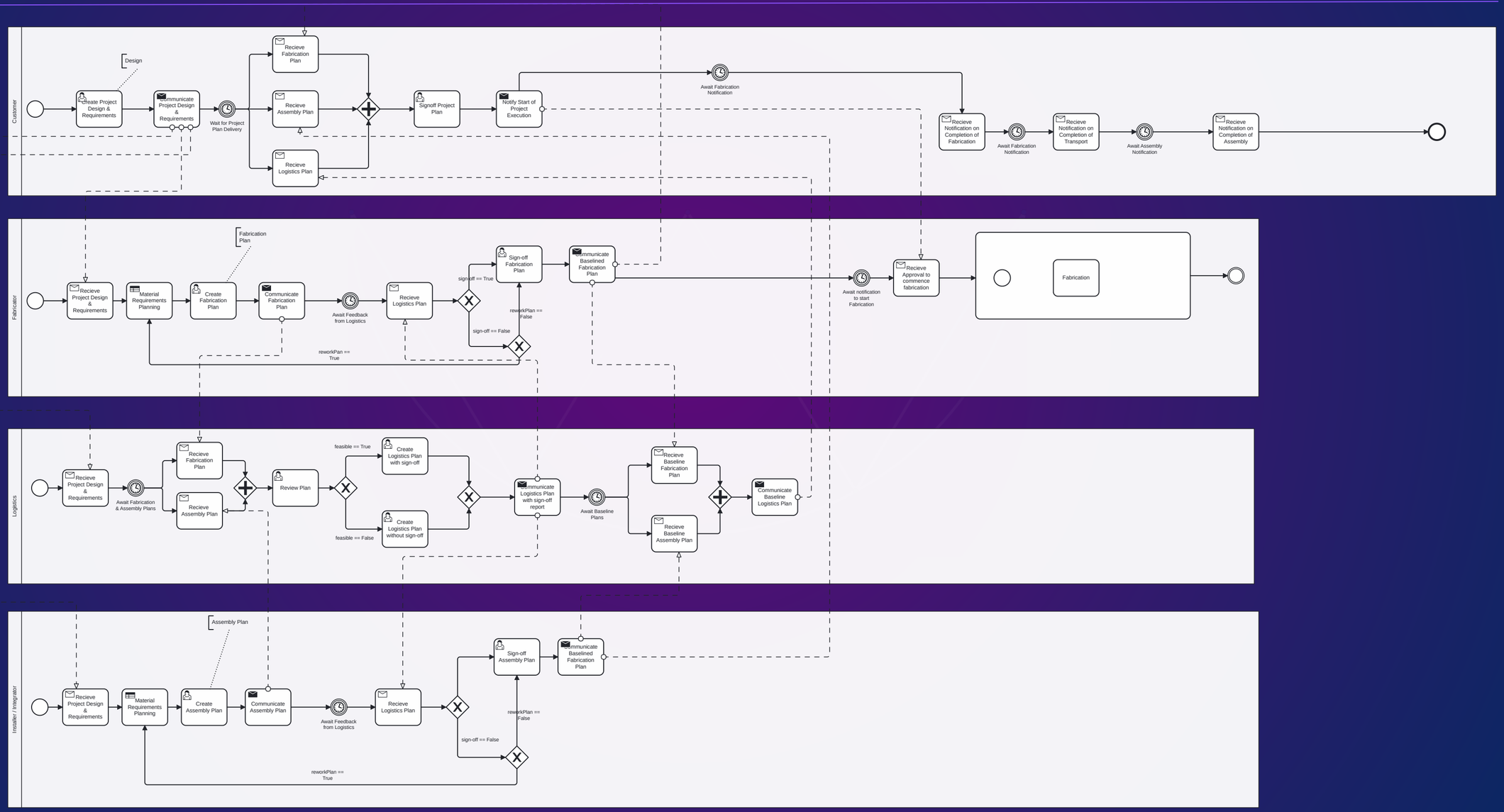
Customer
Design
Create Project Design & Requirements
Communicate Project Design & Requirements
Wait for Project Plan Delivery
Recieve Fabrication Plan
Recieve Assembly Plan
Recieve Logistics Plan
Signoff Project Plan
Notify Start of Project Execution
Await Fabrication Notification
Recieve Notification on Completion of Fabrication
Await Fabrication Notification
Recieve Notification on Completion of Transport
Await Assembly Notification
Recieve Notification on Completion of Assembly
Fabricator
Fabrication Plan
Recieve Project Design & Requirements
Material Requirements Planning
Create Fabrication Plan
Communicate Fabrication Plan
Await Feedback from Logistics
Recieve Logistics Plan
sign-off == True
Sign-off Fabrication Plan
reworkPlan == False
sign-off == False
reworkPlan == True
Communicate Baselined Fabrication Plan
Await notification to start Fabrication
Recieve Approval to commence fabrication
Fabrication
Logistics
Recieve Project Design & Requirements
Await Fabrication & Assembly Plans
Recieve Fabrication Plan
Recieve Assembly Plan
Review Plan
feasible == True
feasible == False
Create Logistics Plan with sign-off
Create Logistics Plan without sign-off
Communicate Logistics Plan with sign-off report
Await Baseline Plans
Recieve Baseline Fabrication Plan
Recieve Baseline Assembly Plan
Communicate Baseline Logistics Plan
Installer / Integrator
Assembly Plan
Recieve Project Design & Requirements
Material Requirements Planning
Create Assembly Plan
Communicate Assembly Plan
Await Feedback from Logistics
Recieve Logistics Plan
Sign-off Assembly Plan
reworkPlan == False
sign-off == False
reworkPlan == True
Communicate Baselined Fabrication Plan

A PLANNING & ASSIGNMENT PROBLEM

DECISION VARIABLES:

- Num Transporters
- Num Storage Slots
- Equipment Availability

CONSTRAINTS:

- Transport Capacity
- Storage Capacity
- Equipment Throughput

OBJECTIVE(s):
Minimise

- Transport Cost
- Assembly Cost
- Equipment Cost

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Multiple & often conflicting objectives

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INVOLVES MULTIPLE ASSETS

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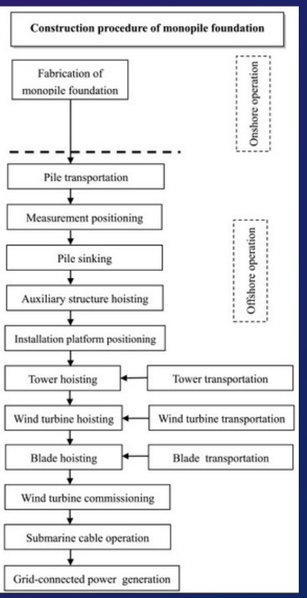
INVOLVES OPERATIONAL PROCEDURES



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Simulation & Optimization

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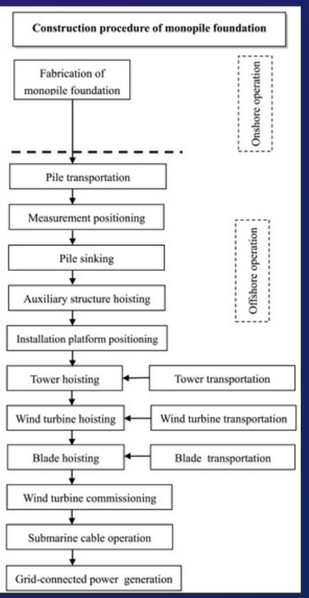
INVOLVES MULTIPLE ASSETS

Sensor Data (Operational Technology, OT)

INVOLVES OPERATIONAL PROCEDURES

Information Techology (IT)



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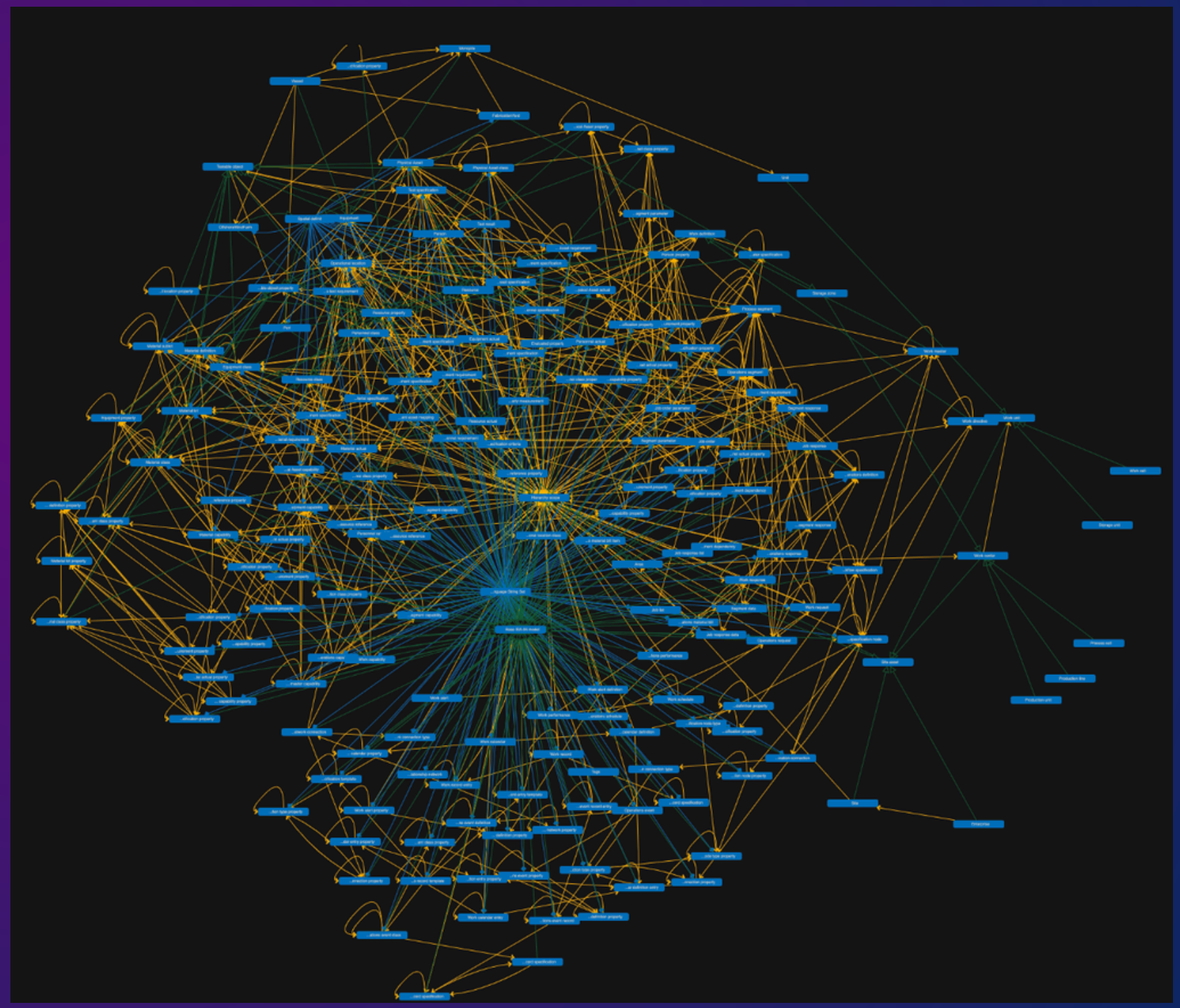
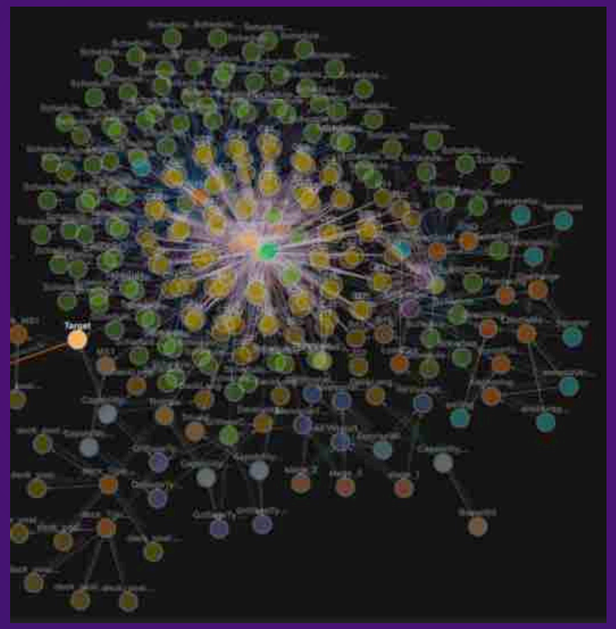
Semantic Model for Convergence of IT /OT



A DIGITAL TWIN FOR WHAT-IF SCENARIO ANALYSIS & OPTIMISATION

Implementation of a simulation & optimisation framework on the digital twin that enables project stakeholders to run what-if scenarios for improved planning & execution

Digitization of assets, processes, operating parameters in their interconnected semantic form to create a digital replica of a logistical process in the maritime industry



Integration of data generated by the physical counterpart with its digital counterpart

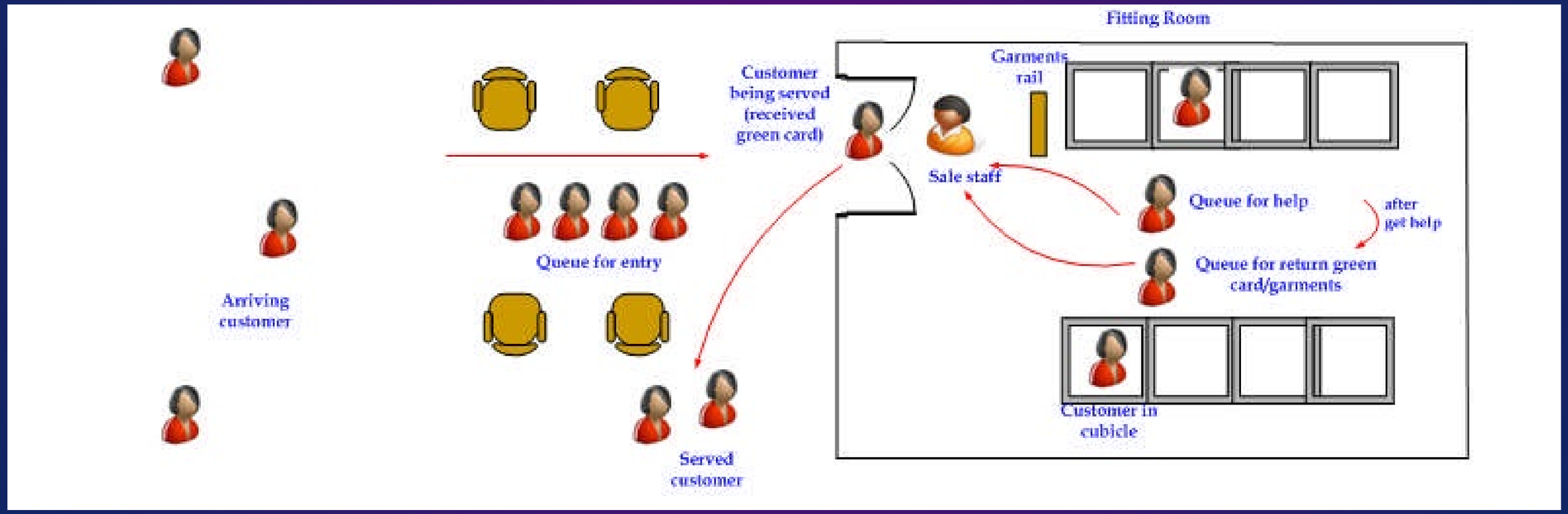
Creation of a System of System (SOS) DT that models and integrates multiple DTs of individual systems, subsystems and components providing a holistic, real-time view of the entire system’s behaviour, performance & responses to various scenarios & conditions

Standardisation of IT/OT data & operational workflows with ISA 95

DIGITAL TWINS & PROCESS OPTIMIZATION

- Semantic model to give higher order meaning to data
- Objects interacting within a system, consist of attributes, relationships with other objects and actionable methods
- Objects can be directly infused as decision objects in optimisation frameworks
- Object interaction (relationships) can be modelled as constraints and/or simulations
- Real time data accessibility for dynamic decision making and updates / dash boarding
- Easy visualization for bottlenecks

HEML AS A QUEUING PROBLEM (DISCRETE EVENT MODEL)



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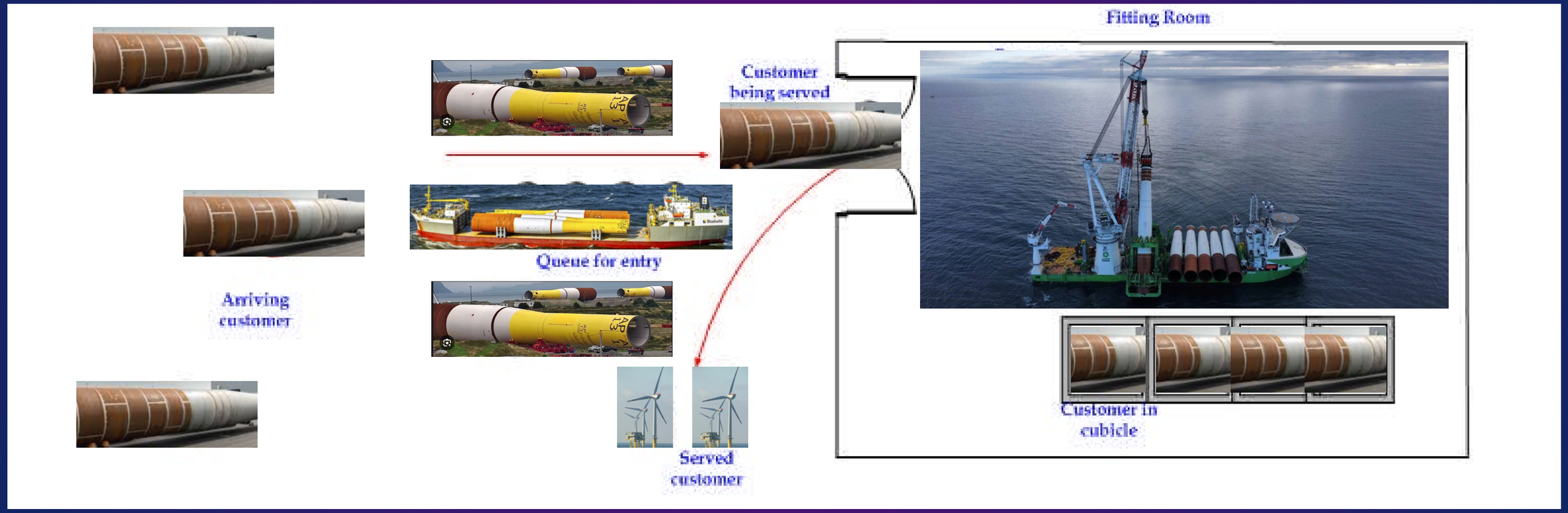
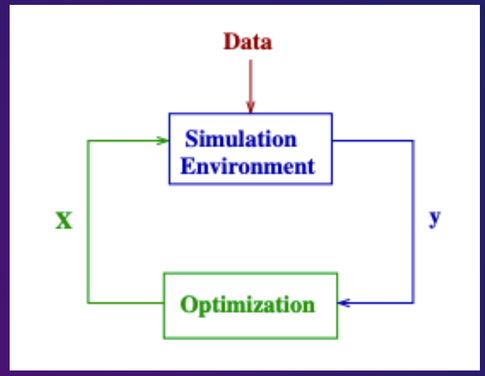


FINDING THE OPTIMAL SOLUTION WITH SIMULATED ANNEALING(SA)

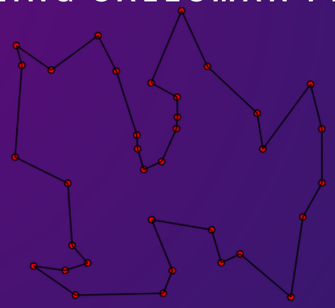
OVERVIEW OF THE OPTIMIZATION PROBLEM

There are two producers S_1 & S_2 which has objects that need to be transported to a consumer D.
The list of objects that S_1 produces is defined with the following ordered collection $\{(A,T_1),(D,T_2),(F,T_3),(H,T_4)\}$ where $T_1 < T_2 < T_3 < T_4$ and indicates the time when the objects will become available
The list of objects that S_2 produces is defined with the following ordered collection $\{(B,T_1),(C,T_3),(E,T_3),(G,T_5)\}$ where $T_1 < T_2 < T_3 < T_4 < T_5$ and indicates the time when the objects will become available
There is one transport Vessel V which is responsible for picking up objects from S_1 & S_2 and delivering to D. The Vessel can carry at most 2 objects at a time. You can choose between S_1 & S_2 as a start condition.
The transportation time, between origin destination pairs, OD = $\{(S_1,S_2,t_1),(S_1,D,t_2),(S_2,D,t_3),(S_2,S_1,t_4),(D,S_1,t_5),(D,S_2,t_6)\}$ is greater than the time difference between the availability time of the objects i.e $delta$ = $\{delta_1 = T_2 - T_1, delta_2 = T_3 - T_2, delta_3 = T_5 - T_3, delta_4 = T_5 - T_4\}$ i.e for t_i in $\{t_1,t_2,t_3,t_4,t_5,t_6\}$ and $delta_j$ in $\{delta_1,delta_2,delta_3,delta_4\}$: $t_i > delta_j$
The consumer D follows a consumption sequence {A, B, C, D, E, F, G} . Any object that arrives out of order at D will not be consumed.

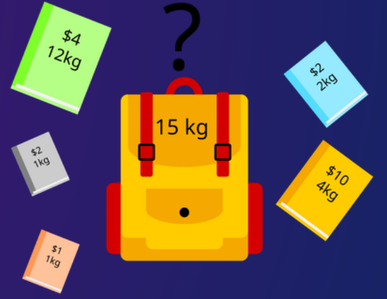


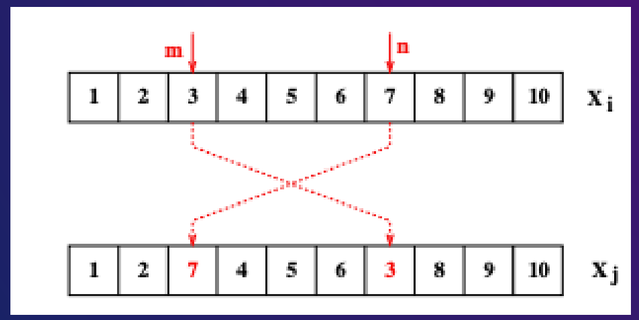
SIMULTANEOUS SIMULATION & PLANNING FRAMEWORK

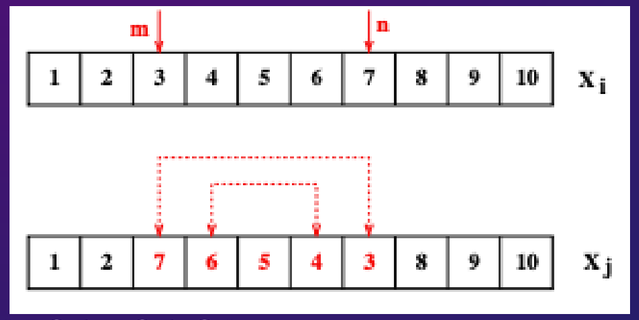
TRAVELLING SALESMAN PROBLEM (TSP)



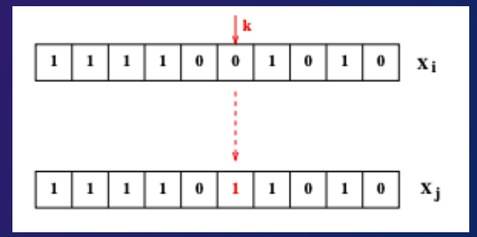
KNAPSACK PROBLEM







TSP - CANDIDATE GENERATION OPERATOR FOR SA



KNAPSACK - CANDIDATE GENERATION OPERATOR FOR SA

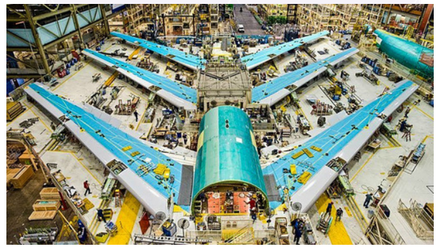
IN A NUTSHELL..

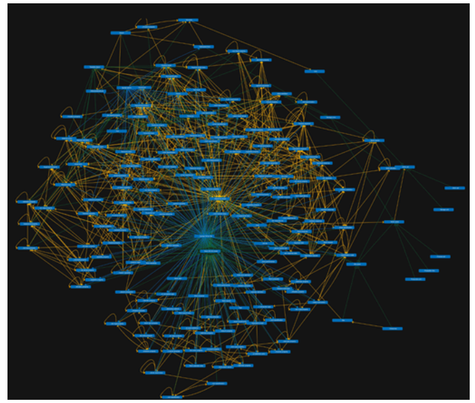
WHAT?

Build a hybrid digital twin to capture & simulate non linear interactions among inventory levels, production rates & resource utilisation while concurrently accommodating the dynamic behaviors of human operators and decision making protocols.

WHY?

- Production Planning & Optimisation is crucial to Manufacturing & Supply Chains
- What-if scenario analysis enables better decision making with multiple trade-offs
- IT/OT convergence leading to granular digital replicas of production processes
- Convergence of Data Driven Models (AI/ML) with Physics Based Models leading to holistic decision support sytems
- Key business KPI is ***efficiency gains from an integrated system***





Ongoing Work

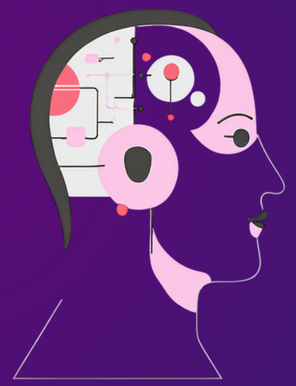
GROUNDING LLMS IN FORMAL SEMANTICS (PDDL)

INPUT PROMPT

The AI agent here is a transporter that can move equipment from one location to another.
*You are a **PDDL** assistant that is helping me design :types*
End your final answers starting with "### TYPES" with the Python dictionary pair '{'name':'description'}'. T he content must be enclosed with ``` ``` comment blocks in PDDL as so:

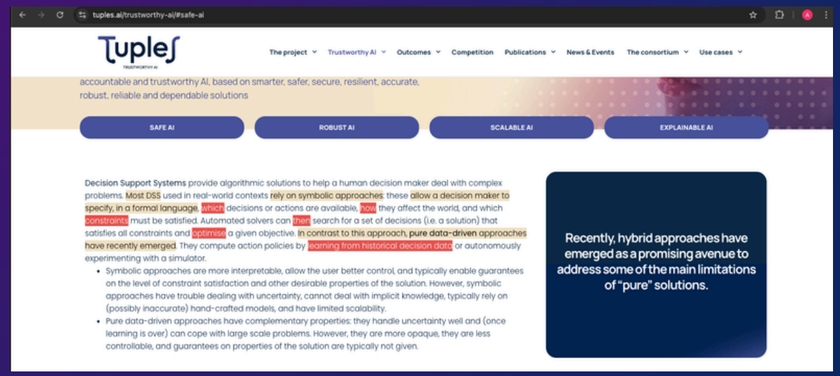
TYPES
```
{
   "type_1": "description",
   "type_2": "description",
   "type_3": "description",
}
```

LLAMA3.2:1b

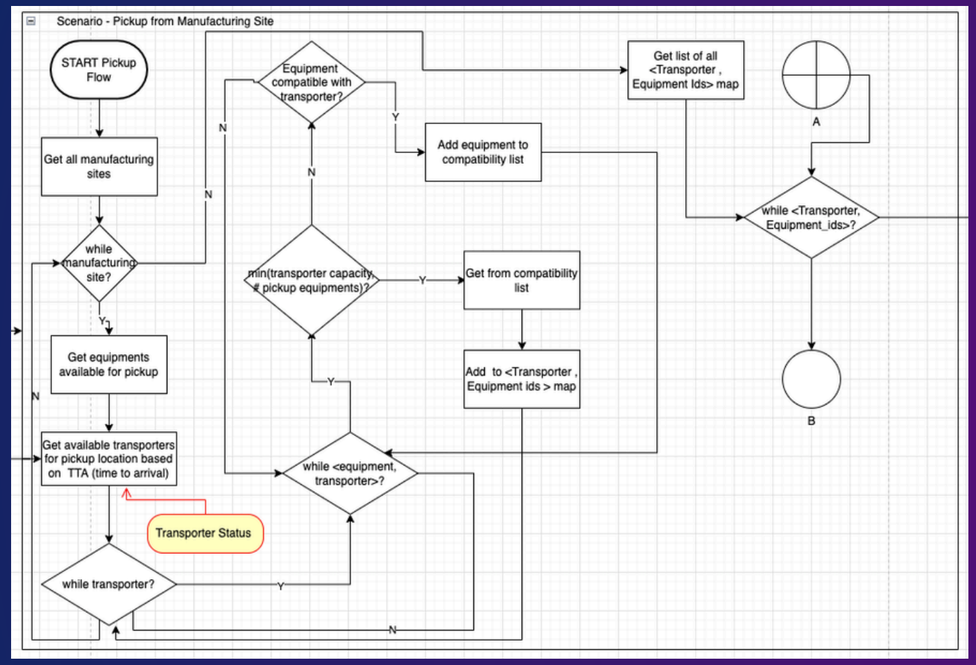


OUTPUT

{'type_1': '; TransportEquipment',
'type_2': '; Load',
'type_3': '; Location'}



PDDL FOR HEML




```
(define (domain PlanningDomain)
  (:requirements :typing :equality :action-costs)
  (:types
                batch - object
                batch_size - batch
                equipment_availability - object
                equipment_part - pickup_location
                location - object
                order - object
                pickup_location - location
                resource_options - object
                transporter - transporter_location
                transporter_availability - object
                transporter_location - location
)
  (:constants

        )


  (:predicates
                (assembly-order ?prev_eqp - equipment_part ?eqp - equipment_part ?complete_order - order)
                (batch_possible ?b - batch)
                (compatible ?eqp - equipment_part ?tp - transporter)
                (eq ?ploc - pickup_location ?tloc - transporter_location)
                (incorporated ?prev_eqp - equipment_part ?complete_order - order)
                (is ?tp - transporter ?tavl - transporter_availability)
                (on ?eqp - equipment_part ?tp - transporter)
                (valid_composition ?b - batch)
                (within_size_limit ?b - batch ?bsl - batch_size)
        )


  (:functions
                (current_batch_size ?b - batch)
                (total-cost )
        )


        (:action get-from-warehouse
                :parameters (?tp - transporter ?eqp - equipment_part ?ploc - pickup_location ?tloc - transporter_location ?prev_eqp - equipment_part ?complete_order - order)
                :precondition (forall (?prev_eqp - equipment_part(pickup_location(location(object))) - equipment_part(pickup_location(location(object)))) (imply (assembly_order ?
prev_eqp - equipment_part ?eqp - equipment_part ?complete_order - order) (incorporated ?prev_eqp - equipment_part ?complete_order - order)))
                :effect (and
                        (on ?eqp ?tp)
                )
        )




)
```

OPTIMISATION - REINFORCEMENT LEARNING & GRAPH BASED PROBLEM FORMULATION

- Comparison of model based and data-driven approaches
- Graph representation learning
- Learned Heuristics vs Model-based heuristics

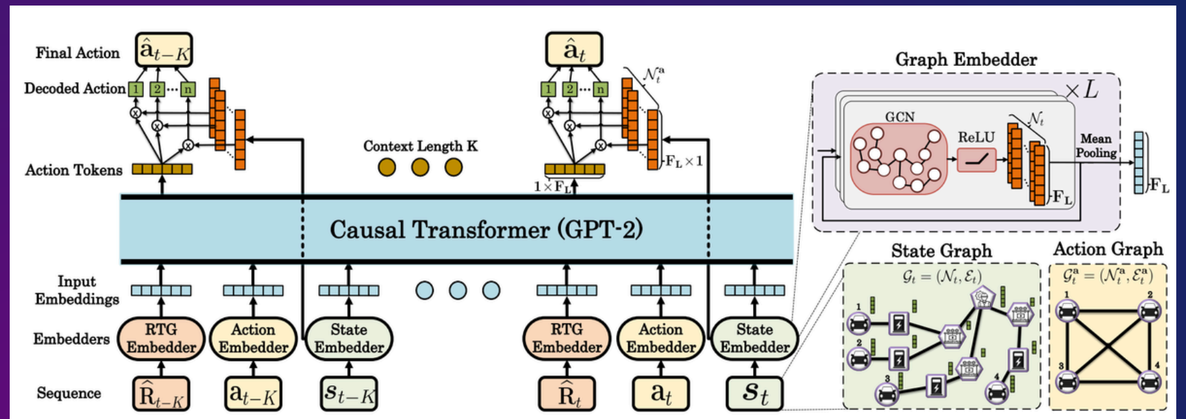
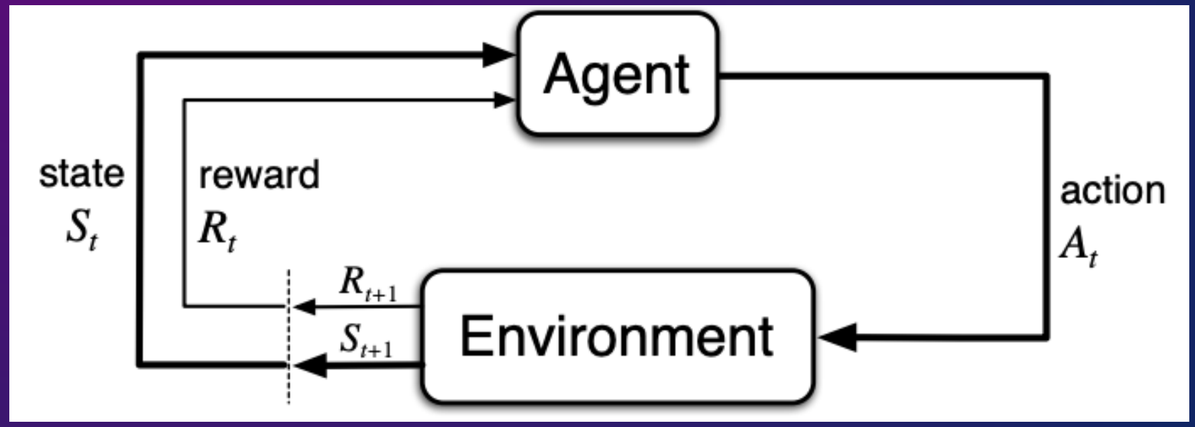


Figure 1: Overview of the GNN-DT architecture. The input sequence, comprising return-to-go, action, and state, is processed through specialized embedding modules. The action graph $\mathcal{G}_t^{\mathbf{a}} = (\mathcal{N}_t^{\mathbf{a}}, \mathcal{E}_t^{\mathbf{a}})$, with nodes $\mathcal{N}_t^{\mathbf{a}} \subset \mathcal{N}_t$, and the state graph $\mathcal{G}_t = (\mathcal{N}_t, \mathcal{E}_t)$ are encoded using GNN-based embedders to produce embeddings of dimension F_L. These embeddings serve as inputs to a GPT-2–based causal transformer, which predicts the next action token. The predicted action token acts as a decoder, generating actions by multiplying with specific GNN state node embeddings.



Thank you!

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