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Decision Guidance Systems and Applications To Manufacturing, Power Grid, Supply Chain and IoT

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ICEIS 2018 Keynote Address

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- Prof. Hanan Mengash, *Group Decision Guidance for Recommenders with Composite Alternatives*, 2016.
- Prof. Hesham Altaleb, *Market-based Decision Guidance for Electric Power Consortia,* 2015.
- Dr. John McDowal, *A Framework for Optimal Service Composition and Execution Based on Business Process Management Notation (BPMN),* 2014 (jointly w/ Prof. Kerschberg)
- Dr. Nathan Egge, *Decision Guidance Query Language (DGQL): Algorithms based on Preprocessing and Continuous Approximations,* 2014.
- Dr. Susan Farley, *Top-k Algorithms for SimQL: A Decision Guidance Query Language Based on Stochastic Simulation,* 2013.
- Prof. Ben Ngan, *A Framework and Algorithms for Multivariate Time Series Analytics: Learning, Monitoring, and Recommendation*, 2013. (jointly with Prof. Lin)
- Dr. Gordon Shao, *Decision Guidance for Sustainable Manufacturing*, 2013. (jointly with Prof. Ammann)
- Dr. Judy Luo, *Regression Learning in Decision Guidance Systems: Models, Languages and Algorithms,* 2012.
- Dr. Khalid Alodhaibi, *Decision-Guided Recommenders with Composite Alternatives,* 2011.
- Dr. Lei Zhang, *Securing the Information Disclosure Process,* 2010. (jointly with Prof. Jajodia)
- Prof. Malak Al-Nury, *Service Composition Framework to Unify Simulation and Optimization in Supply Chains,* 2010.
- Prof. Csilla Farkas, *Secure Databases: Constraints, Inference Channels and Monitoring Disclosures,* 1999. (jointly with Prof. Jajodia)
- Dr. Jia Chen, *Multityped Constraint Algebras and Mathematical Programming in Constraint Databases,* 1999.
- Dr. Victor Segal, *Algorithms, Optimization and Implementation of Constraint Object-Oriented Database System,* 1999.
- Prof. Samuel Varas *On Optimal Constraint Decomposition, Monitoring and Management in Distributed Environments,* 1998. (jointly with Prof. Kerschberg)

Current

- Mohan Krisnamoorthy, *Manufacturing Processes: Languages and Algorithms for Descriptive, Predictive and Prescriptive Analytics.* (jointly with Prof. Menasce)
- M. Omar Nachawati, *Algorithms for Decision Guidance Management System*
- Roberto Levy, *A Decision Guidance Framework for Energy Public Policy and Investment*
- Fernando Boccanera, *Decision Guidance for Healthcare Individual and Group Policy*

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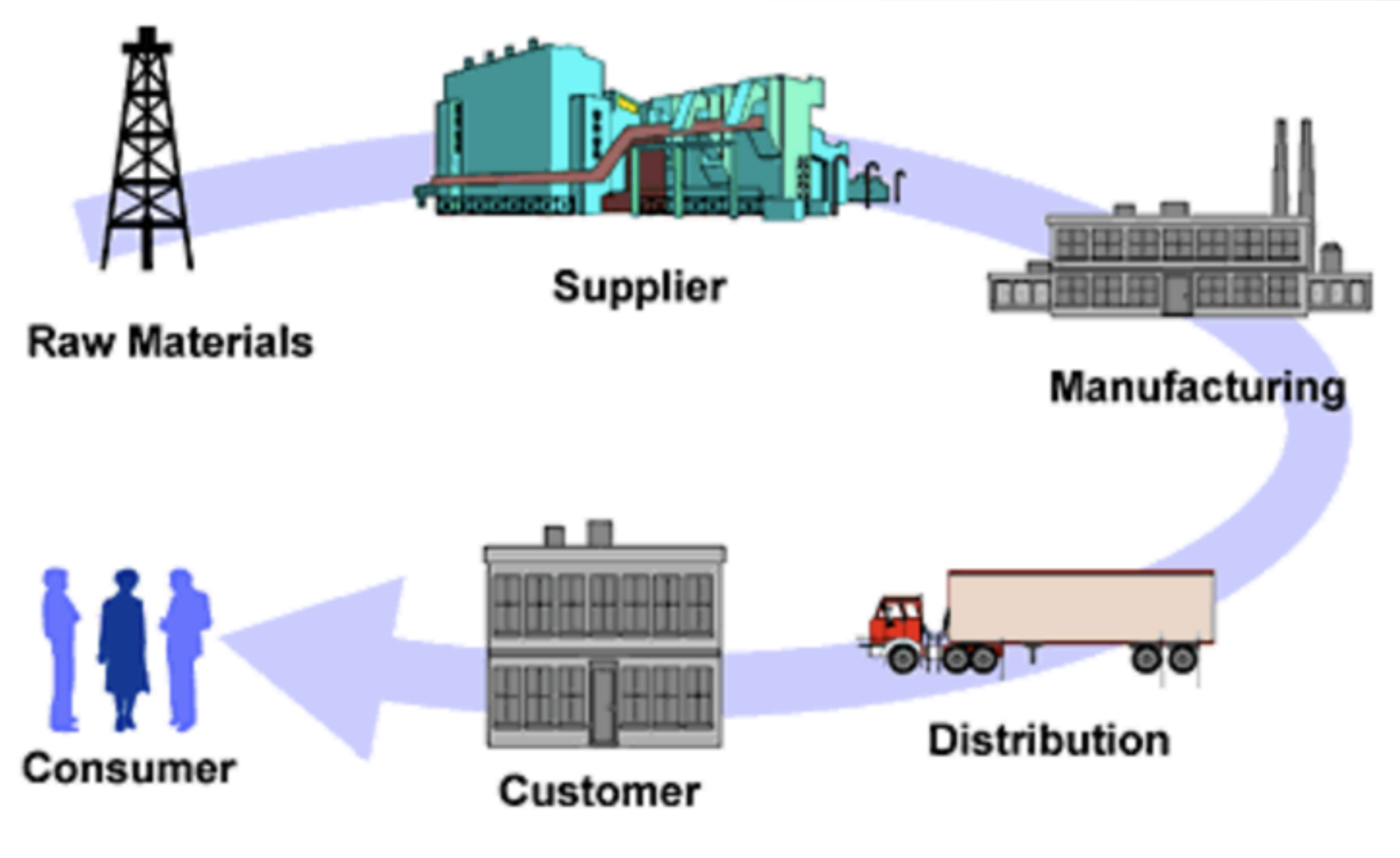
What is it about?

Decision Guidance (DG) systems are a class of decision support systems geared to

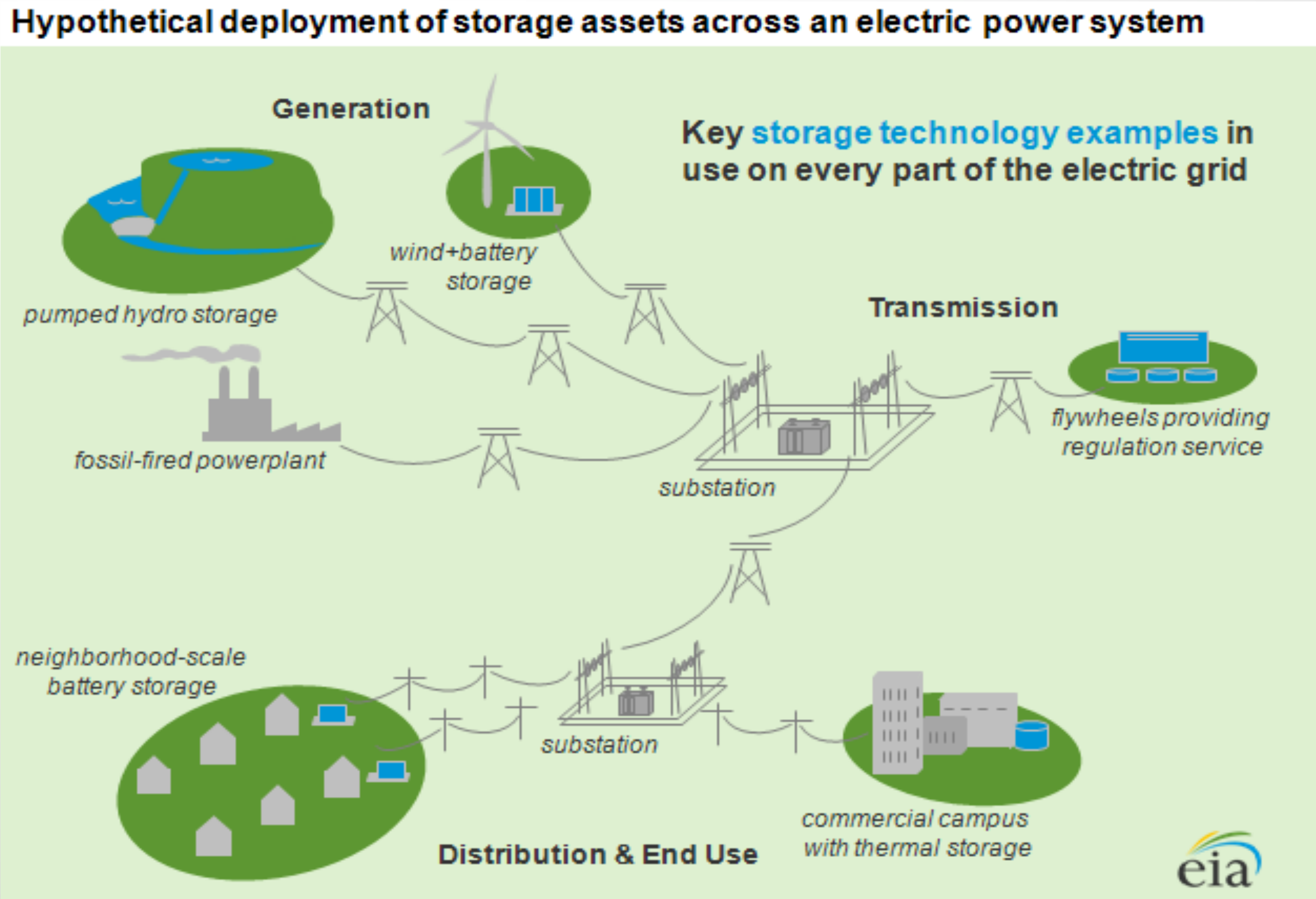
- elicit knowledge from domain experts and
- provide actionable recommendations to human decision-makers,
- with the goal of arriving at the best possible course of action.

Examples of Decision Guidance Systems:
Supply Chain Management



Examples of Decision Guidance Systems:
Renewable Power and Storage

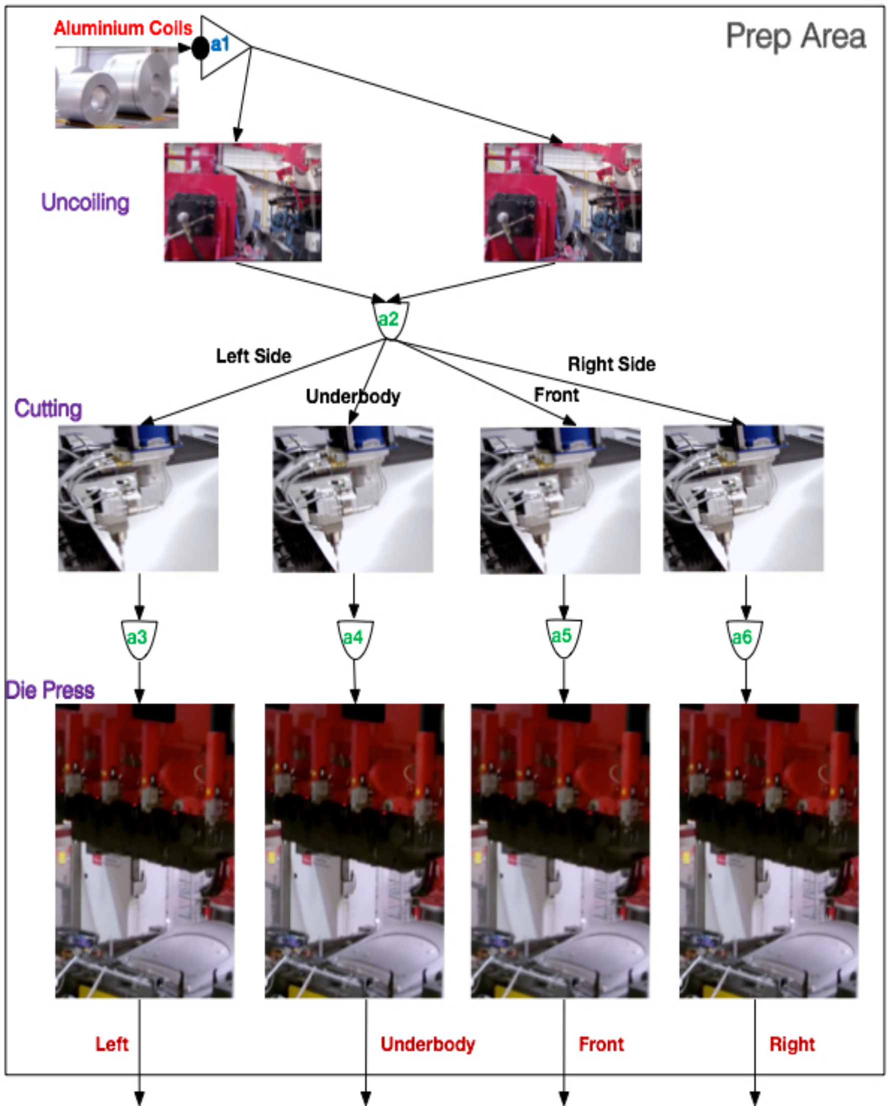
GMU pilot project for Dominion Virginia Power

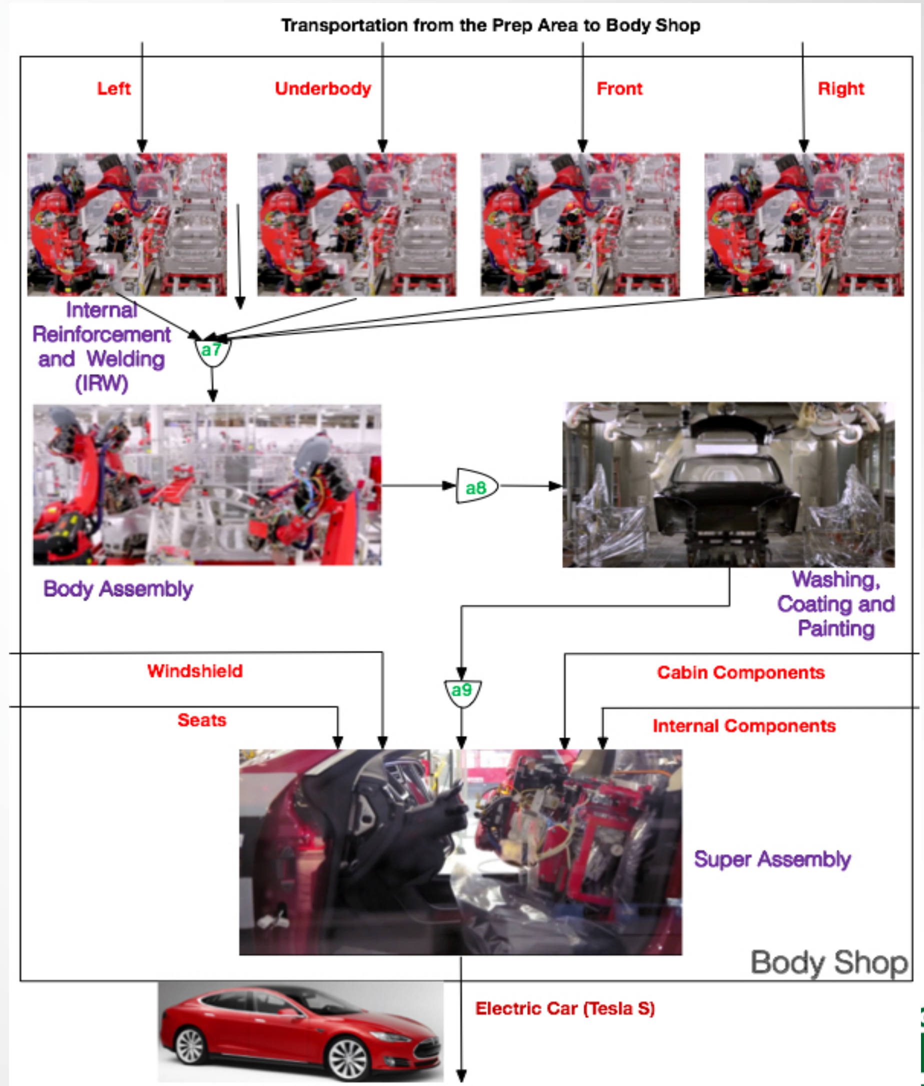


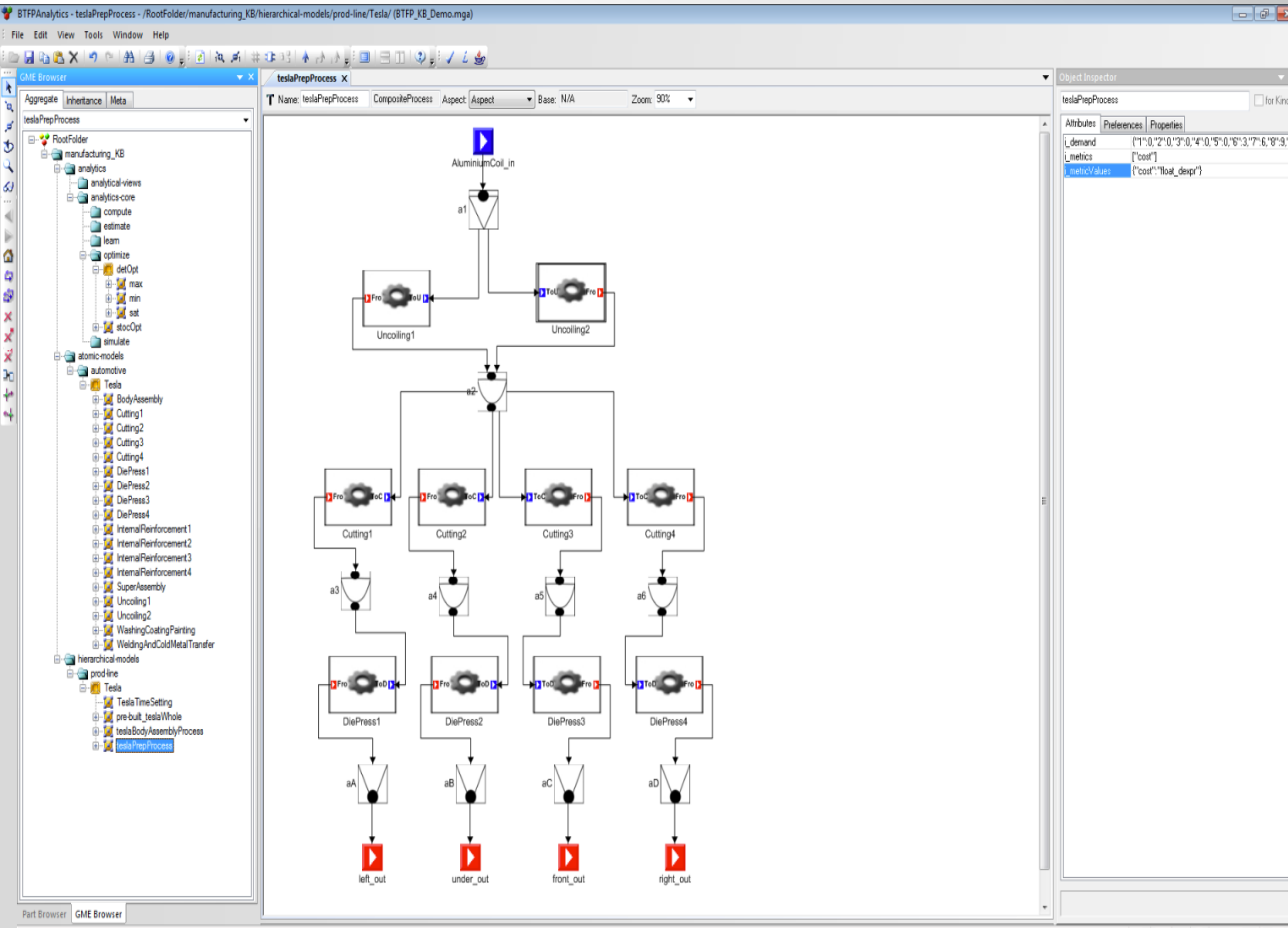
U.S. Energy Information Administration (EIA)

Examples of Decision Guidance Systems:
Tesla prep and body shop

GMU project for the National Institute of Standards & Technology



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i_metricValues {"cost":"float_dexpr"}

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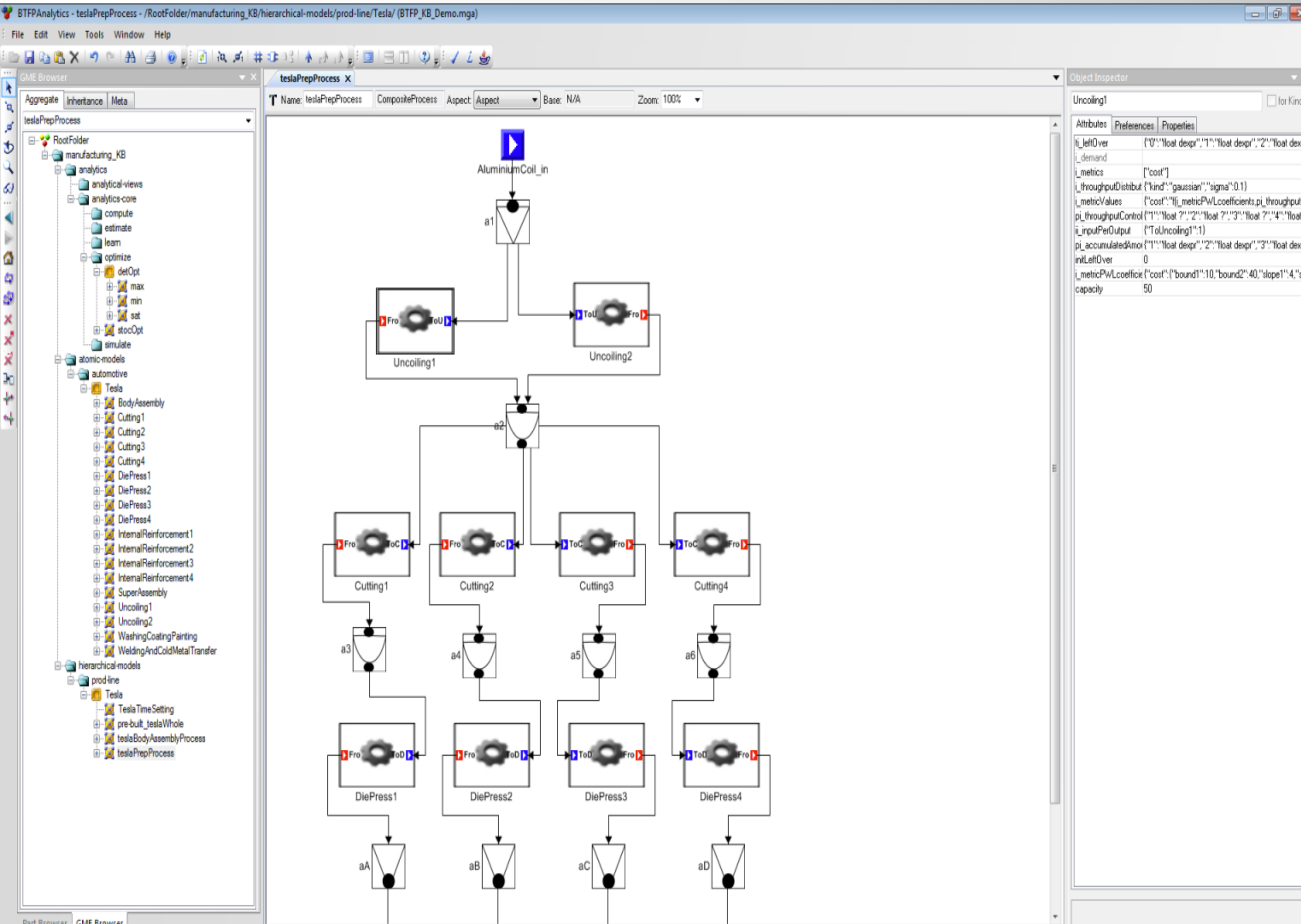

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i_metricValues
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ii_inputPerOutput {"ToUncoiling1":1}
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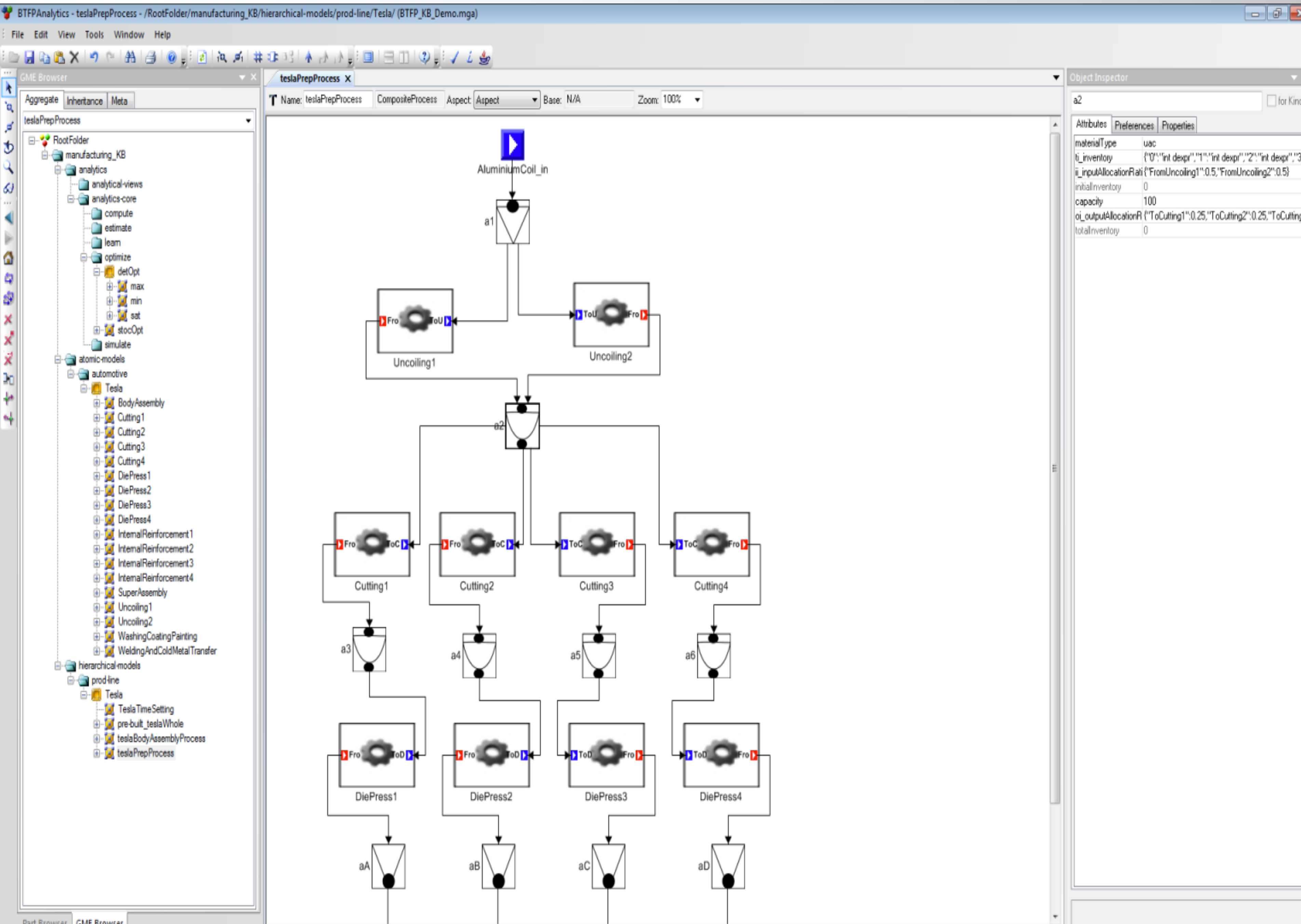

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ti_inventory {"0":"int dexpr","1":"int dexpr","2":"int dexpr","3"
ii_inputAllocationRati {"FromUncoiling1":0.5,"FromUncoiling2":0.5}
initialInventory 0
capacity 100
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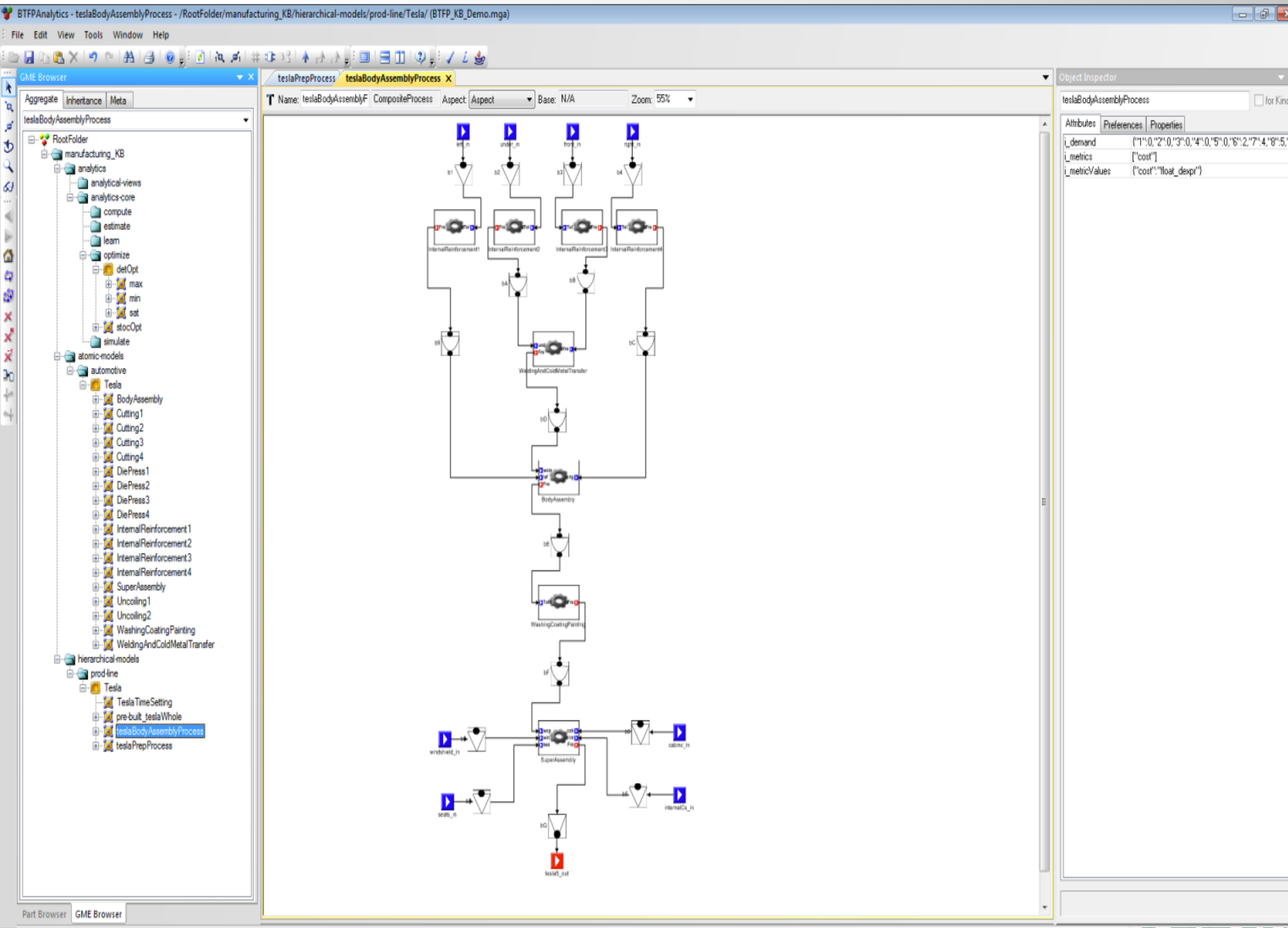

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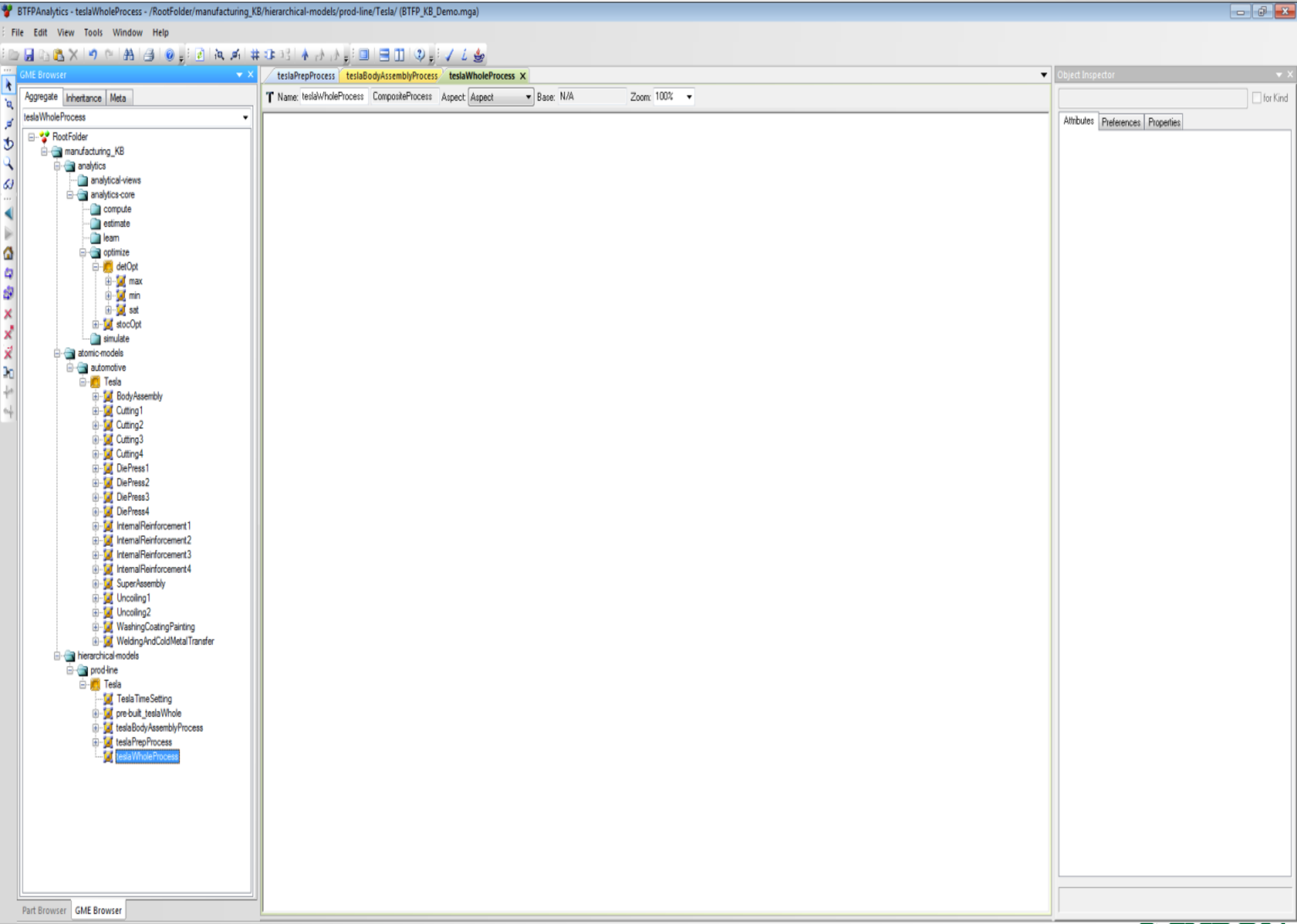
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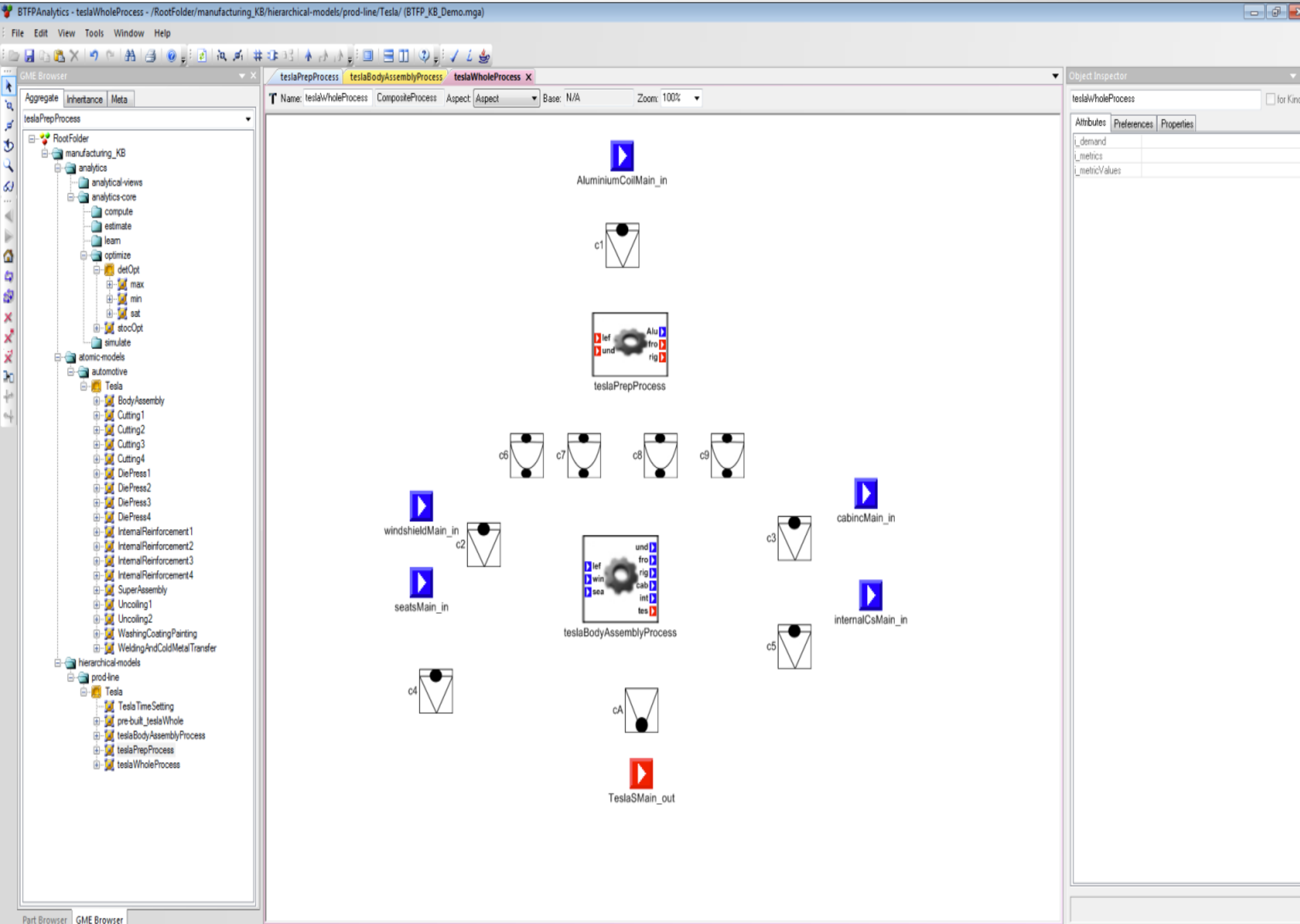
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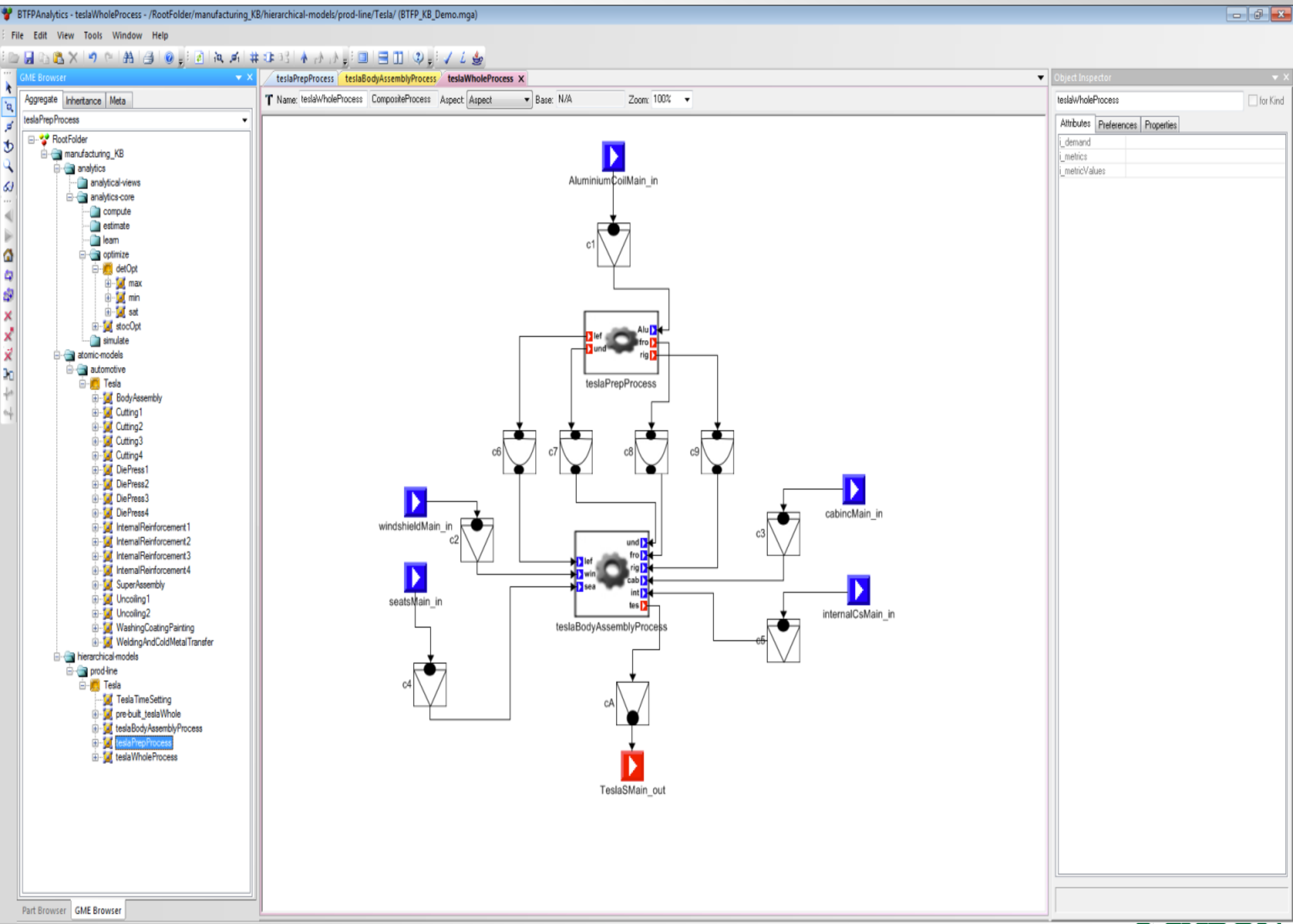
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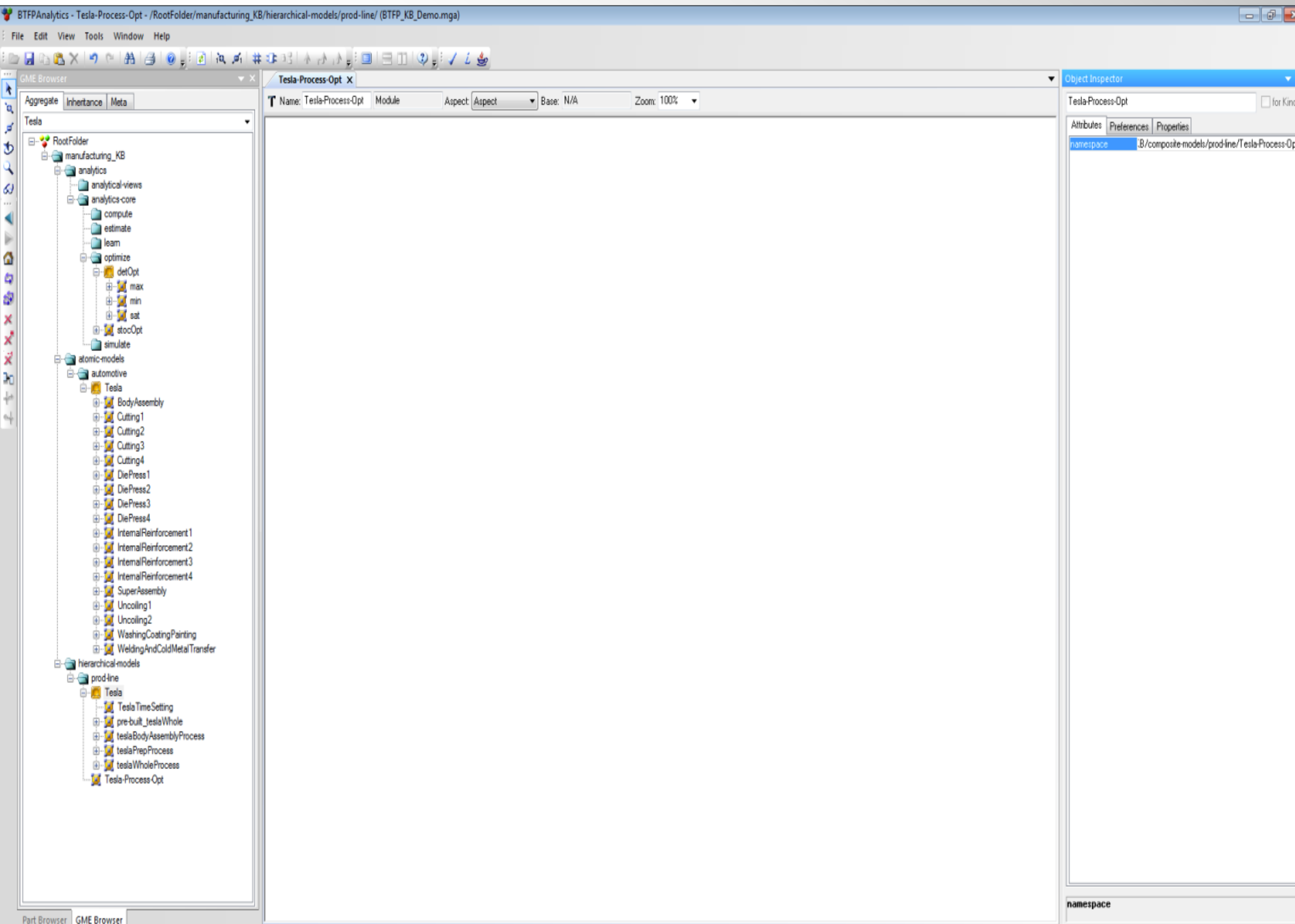
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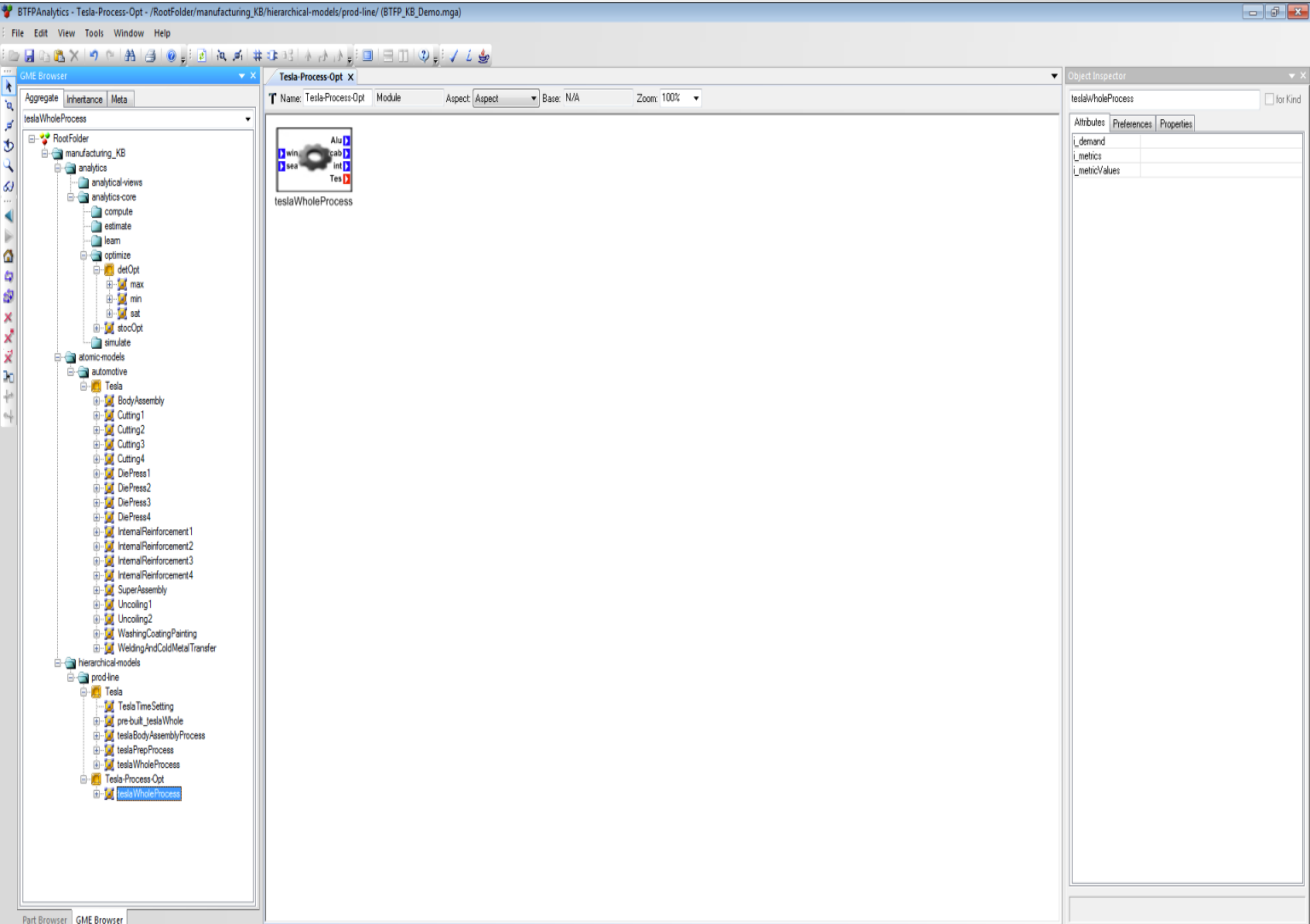
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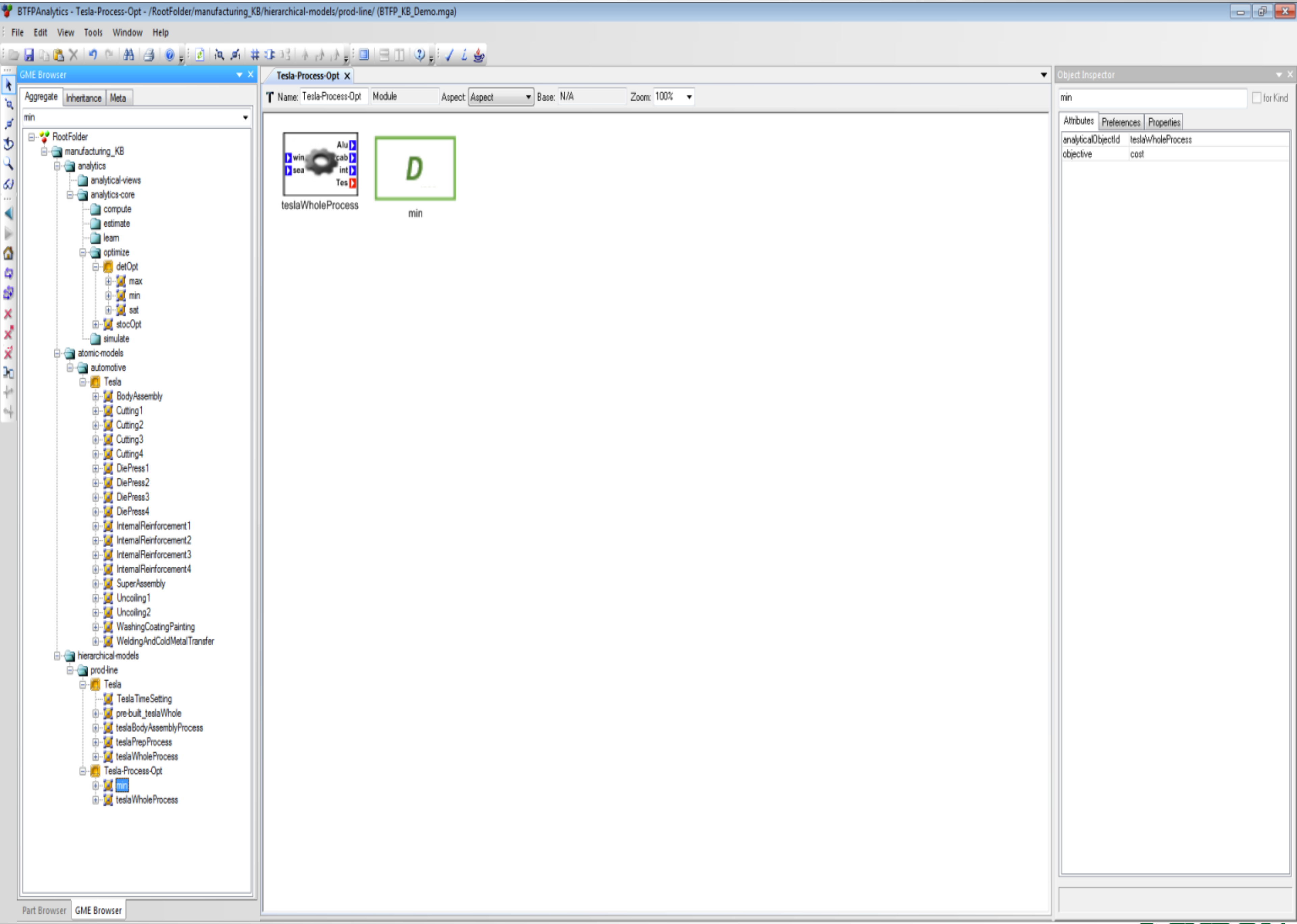
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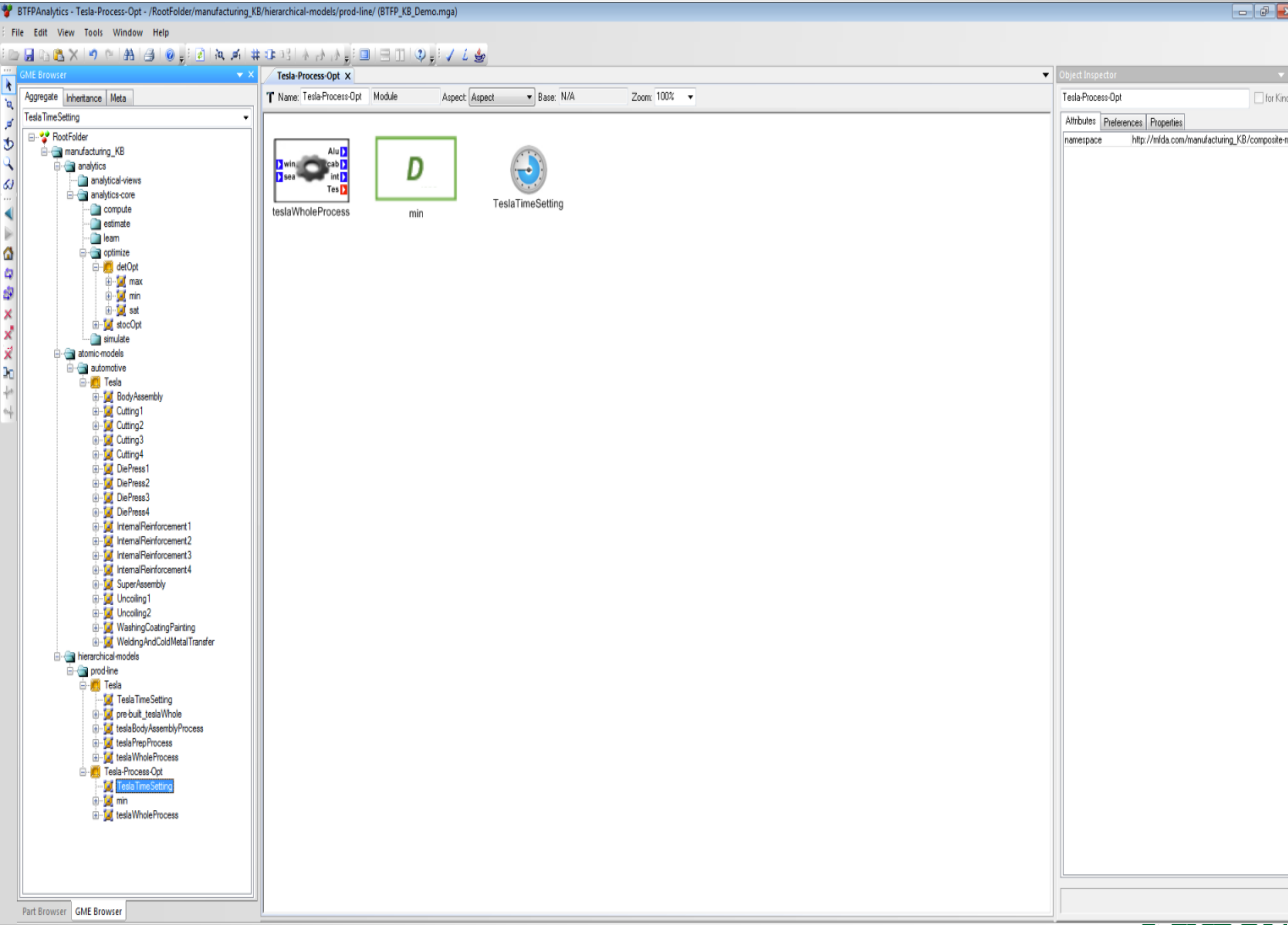
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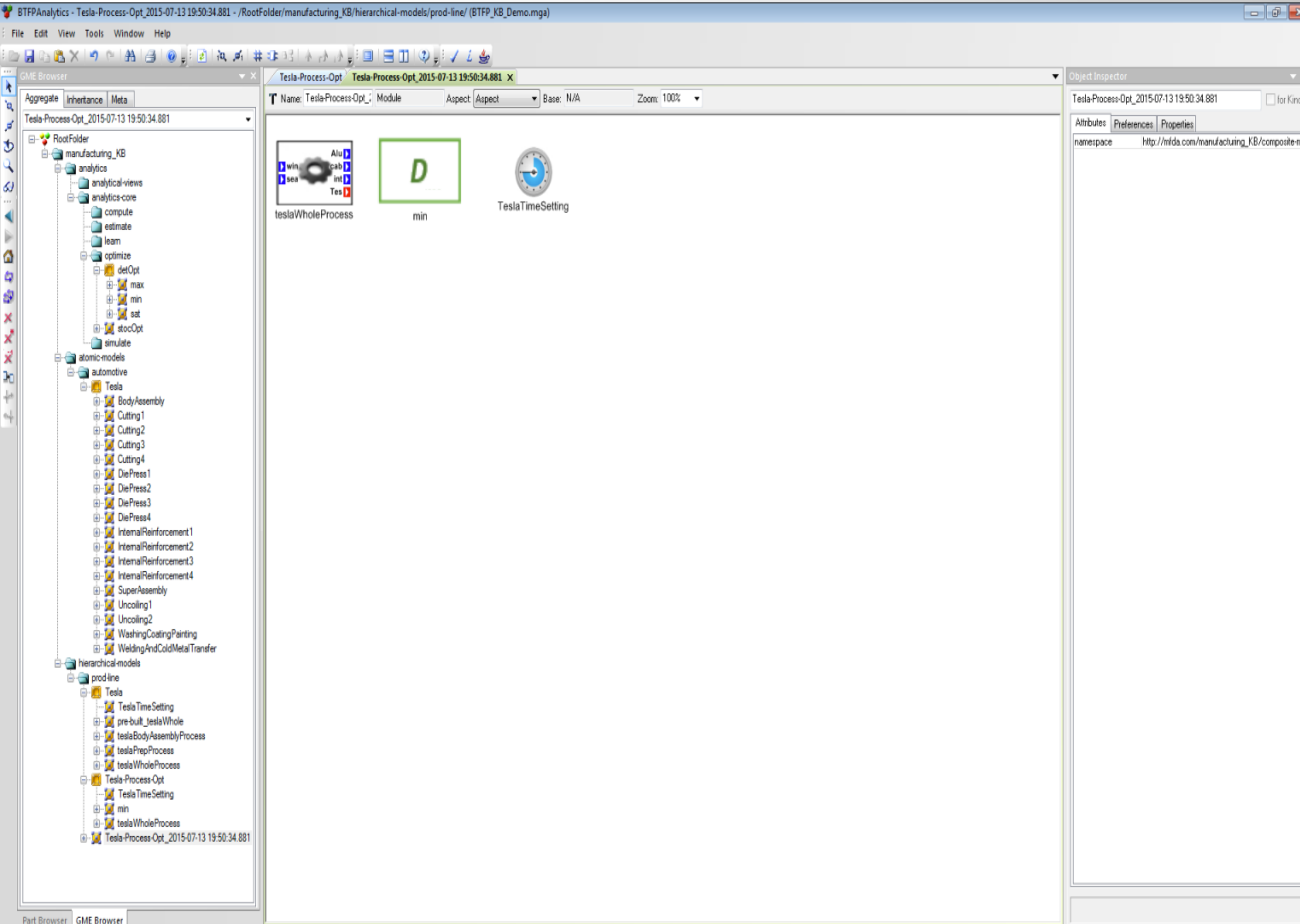
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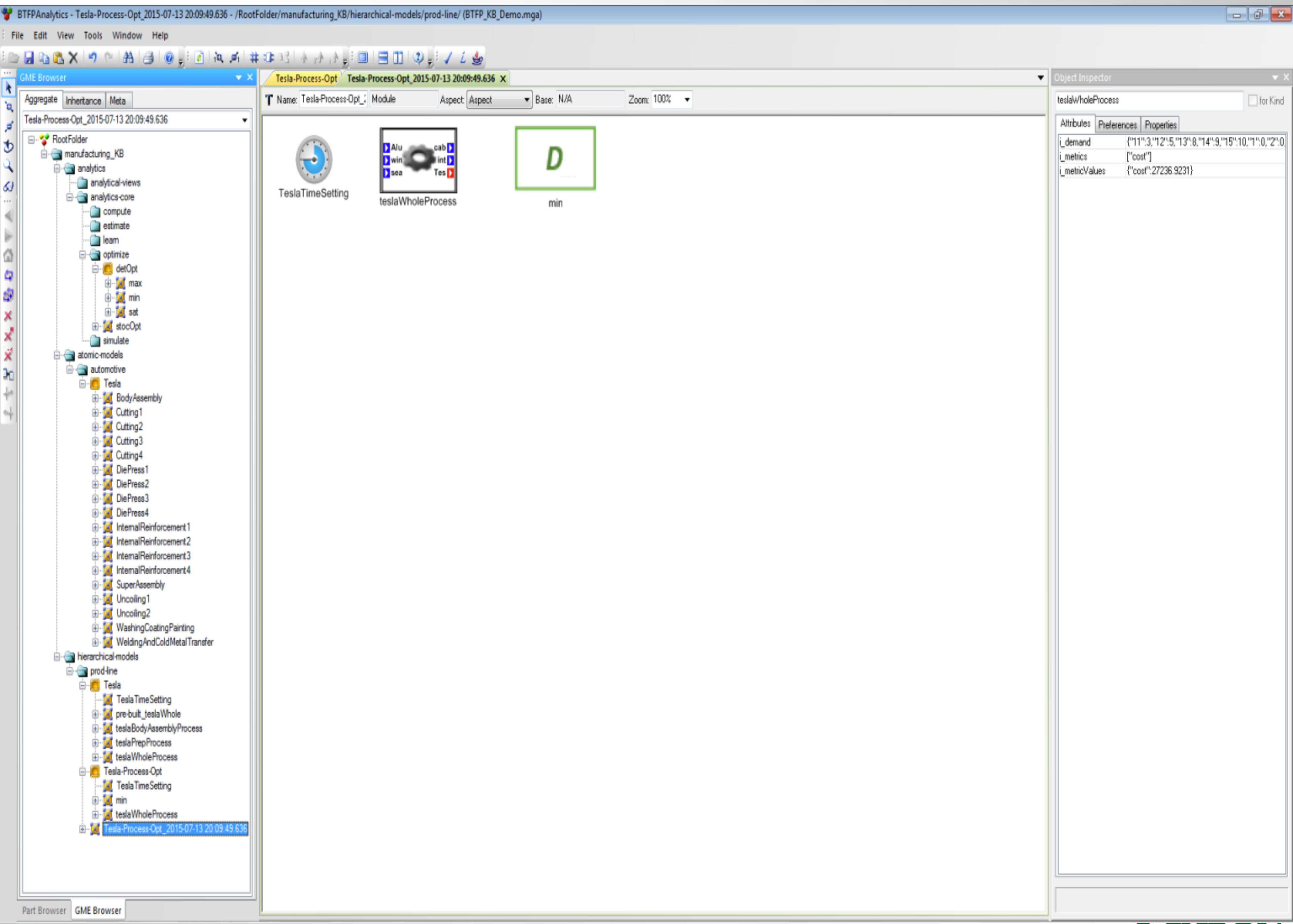

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i_metrics ["cost"]
i_metricValues {"cost":27236.9231}

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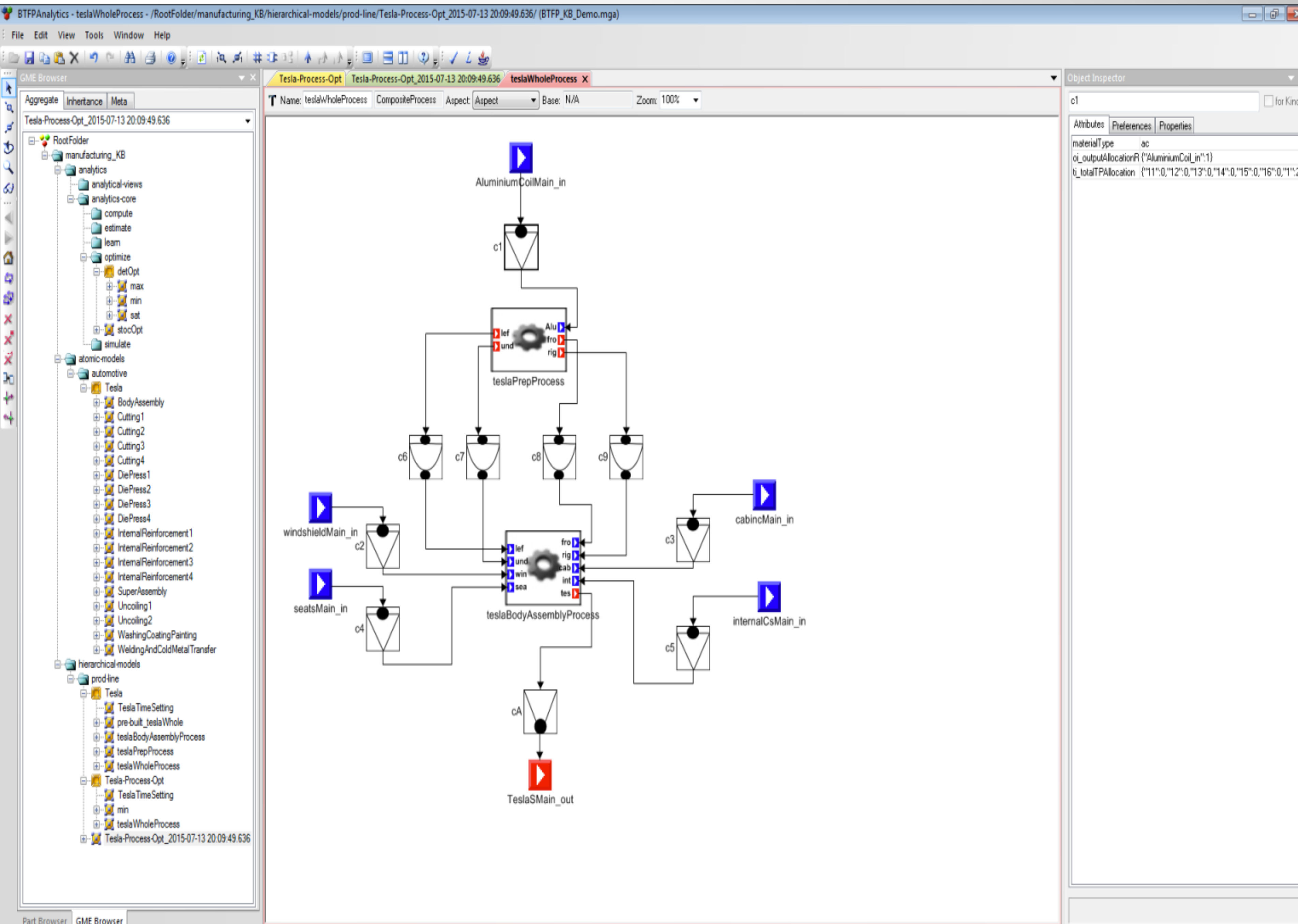

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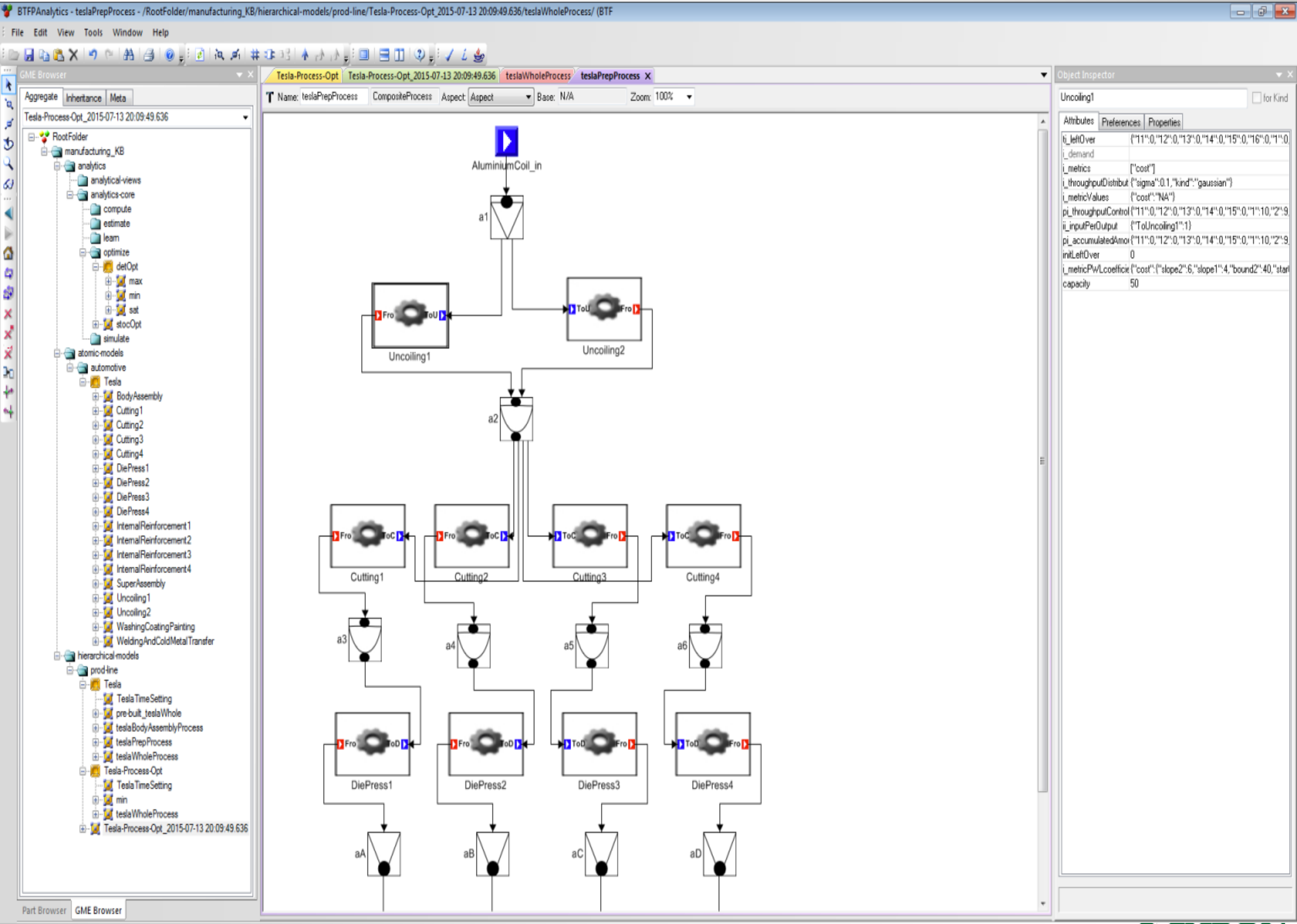

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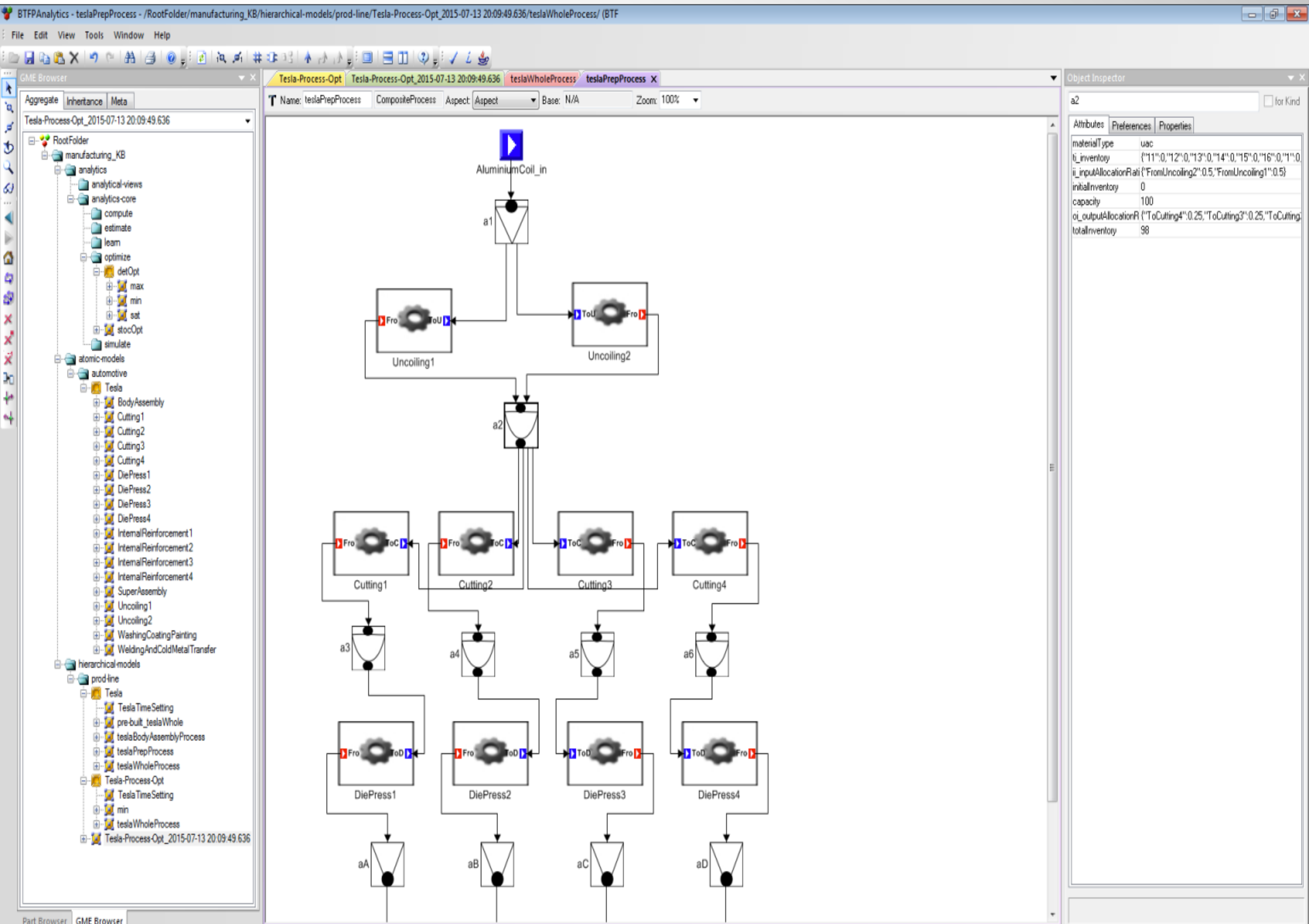

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initialInventory 0
capacity 100
oi_outputAllocationR {"ToCutting4":0.25,"ToCutting3":0.25,"ToCutting
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Outline

- DG systems: need, challenges, vision
- DG language & tool example:
  - DG Analytics Language (DGAL) & Management System (Unity DGMS)
- DG application example:
  - Manufacturing and supply service networks based on model repository
- DG algorithm example:
  - Optimizing multistage service networks based on preprocessing and decomposition
- Broader view on DG research: languages/tools, algorithms, applications
- Three grand challenges:
  - IoT + DG = (Smart) Cyber Physical Service Networks
  - Design (e.g., product, process, architectural, …) + DG = (Smart) Parametric Design
  - Public policy (e.g., renewable energy) + DG + Group decision methods = (Smart) public policy
- Conclusions

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Decision Guidance Systems (DGS)

DGS need to

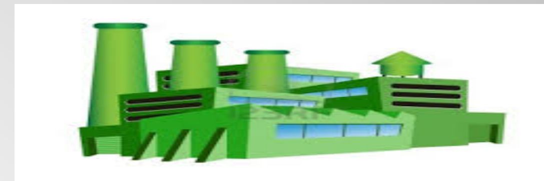
- use and mine large amounts of data
- elicit knowledge about model structure from domain experts
- learn deterministic or stochastic models
- elicit metrics, KPI and decision objectives
- perform analysis tasks, incl. monitoring, diagnosis, prediction, optimization
- explain actionable recommendations to decision-makers
- solicit decision-makers feedback for iterative improvement

Descriptive Analytics Tasks

Predictive Analytics Tasks

Diagnostic Analytics Tasks

Prescriptive/ Optimization Analytics Tasks



Domain Specific Modeling & Analytics GUI

Interfaces / Mappers

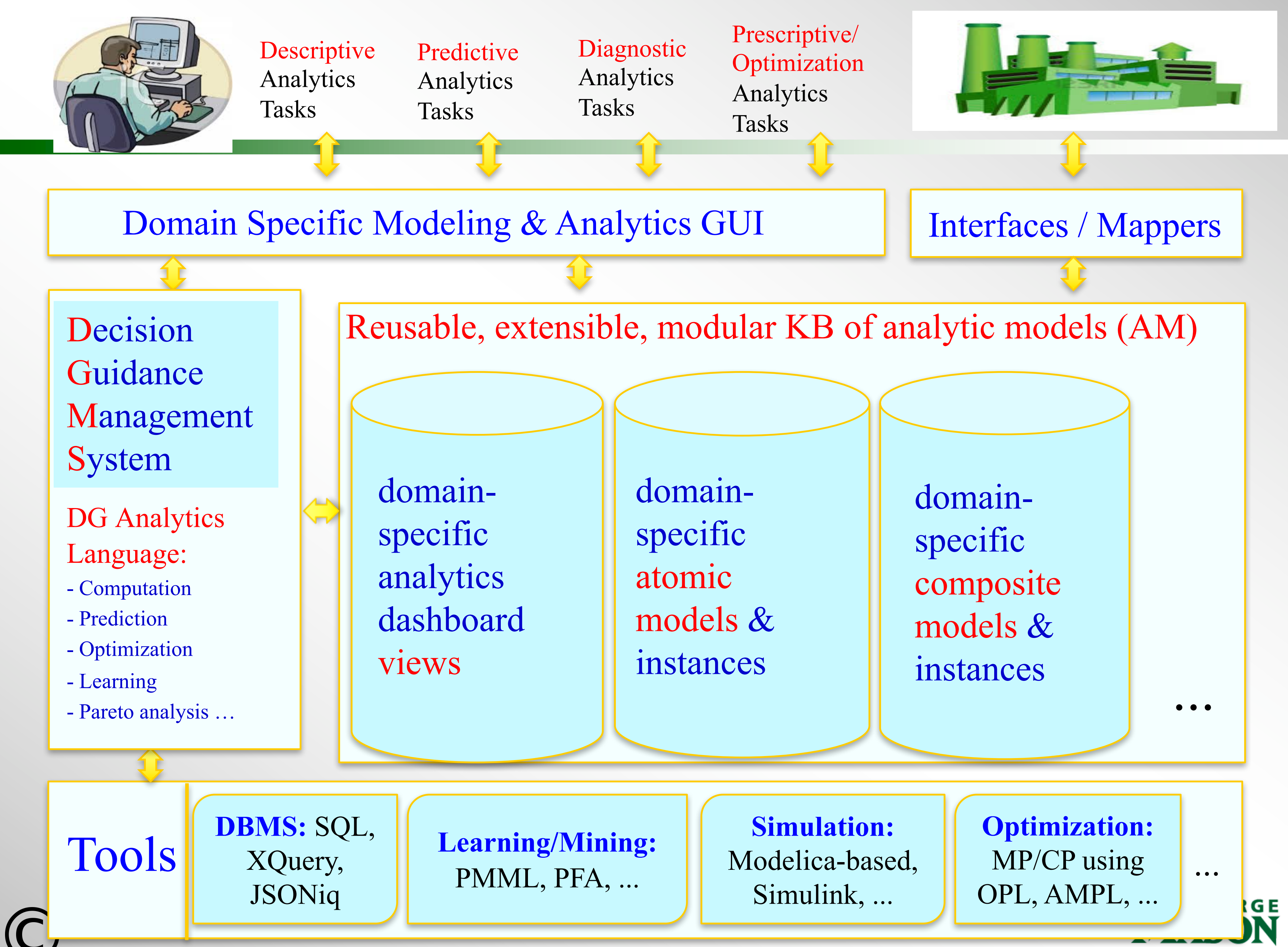
?

TODAY every task is implemented:

- one off
- from scratch
- non-reusable
- non-modular
- requires math, OR, IT & domain-specific expertise
- high cost
- long development cycle
- difficult to modify/extend

Tools

DBMS: SQL, XQuery, JSONiq	**Learning/Mining:** PMML, PFA, ...	**Simulation:** Modelica-based, Simulink, ...	**Optimization:** MP/CP using OPL, AMPL, ...	…


Descriptive Analytics Tasks
Predictive Analytics Tasks
Diagnostic Analytics Tasks
Prescriptive/ Optimization Analytics Tasks
Domain Specific Modeling & Analytics GUI
Interfaces / Mappers
Decision Guidance Management System
DG Analytics Language:
- Computation
- Prediction
- Optimization
- Learning
- Pareto analysis …
Reusable, extensible, modular KB of analytic models (AM)
domain-specific analytics dashboard views
domain-specific atomic models & instances
domain-specific composite models & instances
…
Tools
DBMS: SQL, XQuery, JSONiq
Learning/Mining: PMML, PFA, ...
Simulation: Modelica-based, Simulink, ...
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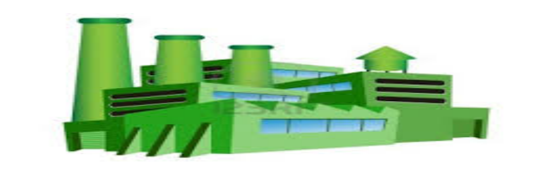
Descriptive Analytics Tasks

Predictive Analytics Tasks

Diagnostic Analytics Tasks

Prescriptive/ Optimization Analytics Tasks



Domain Specific Modeling & Analytics GUI

Interfaces / Mappers

Decision Guidance Management System

DG Analytics Language:

- Computation
- Prediction
- Optimization
- Learning
- Pareto analysis …

Reusable, extensible, modular KB of analytic models (AM)

- analytical-views
  - dashboards
  - diagnostics
  - monitors
  - param-calibration
  - process-metrics
  - scheduling
  - unit-optimization
  - what-if-analysis

- atomic-models
  - additive
  - casting
  - forming
  - joining
  - machining
  - molding

- process-models
  - factory
    - manuf-cell
    - manuf-unit
    - prod-line
    - templates

…

Tools

DBMS: SQL, XQuery, JSONiq

Learning/Mining: PMML, PFA, ...

Simulation: Modelica-based, Simulink, ...

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...

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- Conclusions

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Background: JSON (Java Script Object Notation) and JSONiq query language

Data format/ model	Query/data manipulation language	Type of data	Used for	Comments
Relational (tabular)	SQL	• structured • flat tables • human readable	Relational databases, such as Oracle, SQL server	• dominant in Buz Info Sys • Not as data interchange format
XML	XQuery	• semi-structured • User-defined tags, HTML-like for data • hierarchical • human and machine readable	• data interchange • web-services	• Popular • Verbose
JSON	JSONiq = SQL for NoSQL stores	• semi-structured • objects = key-values pairs • hierarchical • human and machine readable • compact as compared to XML	• lightweight data interchange • web-services • REST SOA • IoT stack • Data in NoSQL stores, incl. MongoDB,	• Highly popular • Identical w/JS data model • similar Python & Java data models • Dominant in REST, IoT, asynchronous client/server communication, replacing XML

P: fixed params
V: control params

AM

M: metrics
C: constraints

P: fixed params
V: control params

AM

M: metrics
C: constraints

```json
{
  "demand": {"chair": 16, "table": 4},
  "purchaseInfo": {
      "ppu": { "supplier1": {"chair": 50.00, "table": 110.00},
               "supplier2": {"chair": 60.00, "table": 100.00}
      },
      "available": { "supplier1": {"chair": 15, "table": 3},
                     "supplier2": {"chair": 20, "table": 2}
      },
      "qty": { "supplier1": {"chair": 10, "table": 2},
               "supplier2": {"chair": 20, "table": 2}
      }
  }
}
```

```json
{
  "cost": 2120,
  "constraints": true
}
```

P: fixed params
V: control params

AM

M: metrics
C: constraints

```
declare function procurementPM($procurementInput) {
let $demand := $procurementInput.demand,
    $suppliers := keys($procurementInput.purchaseInfo.ppu),
    $ppu := $procurementInput.purchaseInfo.ppu,
    $available := $procurementInput.purchaseInfo.available,
    $qty := $procurementInput.purchaseInfo.qty
let $cost := sum ( for $s in $suppliers, $i in keys($qty($s) )
                   return $ppu($s)($i) * $qty($s)($i)
              )
let $availabilityConstraint := (
      every $s in $suppliers, $i in keys($qty($s))
      satisfies ( $qty($s)($i) <= $available($s)($i) )
    )
let $supply := {|
      for $i in keys($demand)
      return {$i: sum ( for $s in $suppliers return $qty($s)($i) )}
    |}
let $demandSatisfiedConstraint :=
      every $i in keys($demand)
      satisfies $demand($i) <= $supply($i)
let $feasibilityConstraint :=
      $availabilityConstraint and $demandSatisfiedConstraint
return { cost: $cost, constraints: $feasibilityConstraint }
};
```

P: fixed params
V: control params

AM

M: metrics
C: constraints

```json
{
  "demand": {"chair": 16, "table": 4},
  "purchaseInfo": {
      "ppu": { "supplier1": {"chair": 50.00, "table": 110.00},
               "supplier2": {"chair": 60.00, "table": 100.00}
      },
      "available": { "supplier1": {"chair": 15, "table": 3},
                     "supplier2": {"chair": 20, "table": 2}
      },
      "qty": { "supplier1": {"chair": 10, "table": 2},
               "supplier2": {"chair": 20, "table": 2}
      }
  }
}
```

```json
{
  "cost": 2120,
  "constraints": true
}
```


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P: fixed params
V: control params

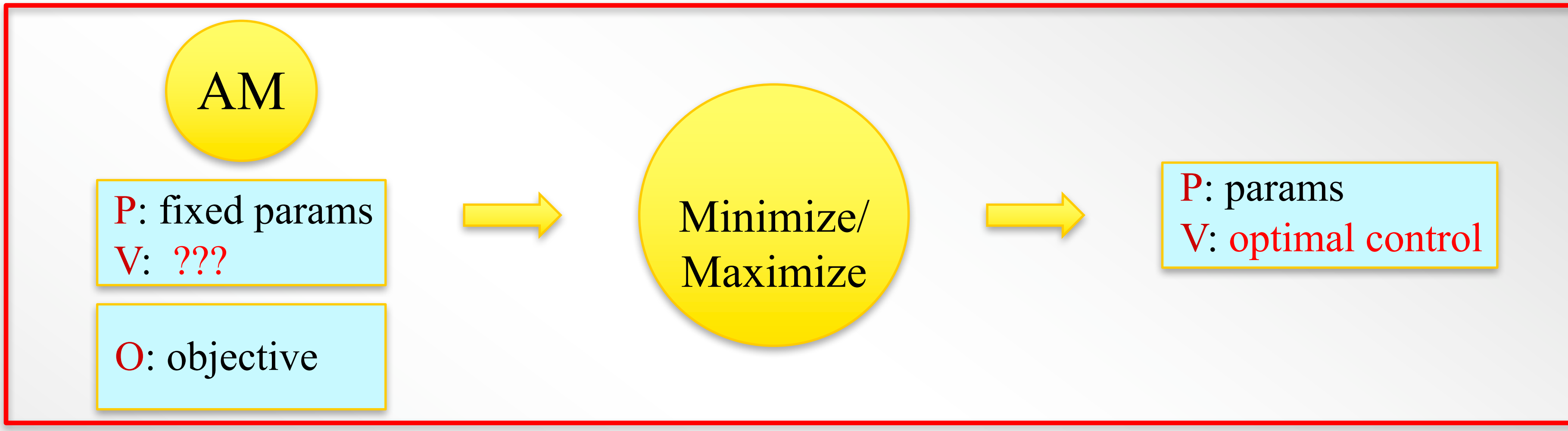
AM

M: metrics
C: constraints

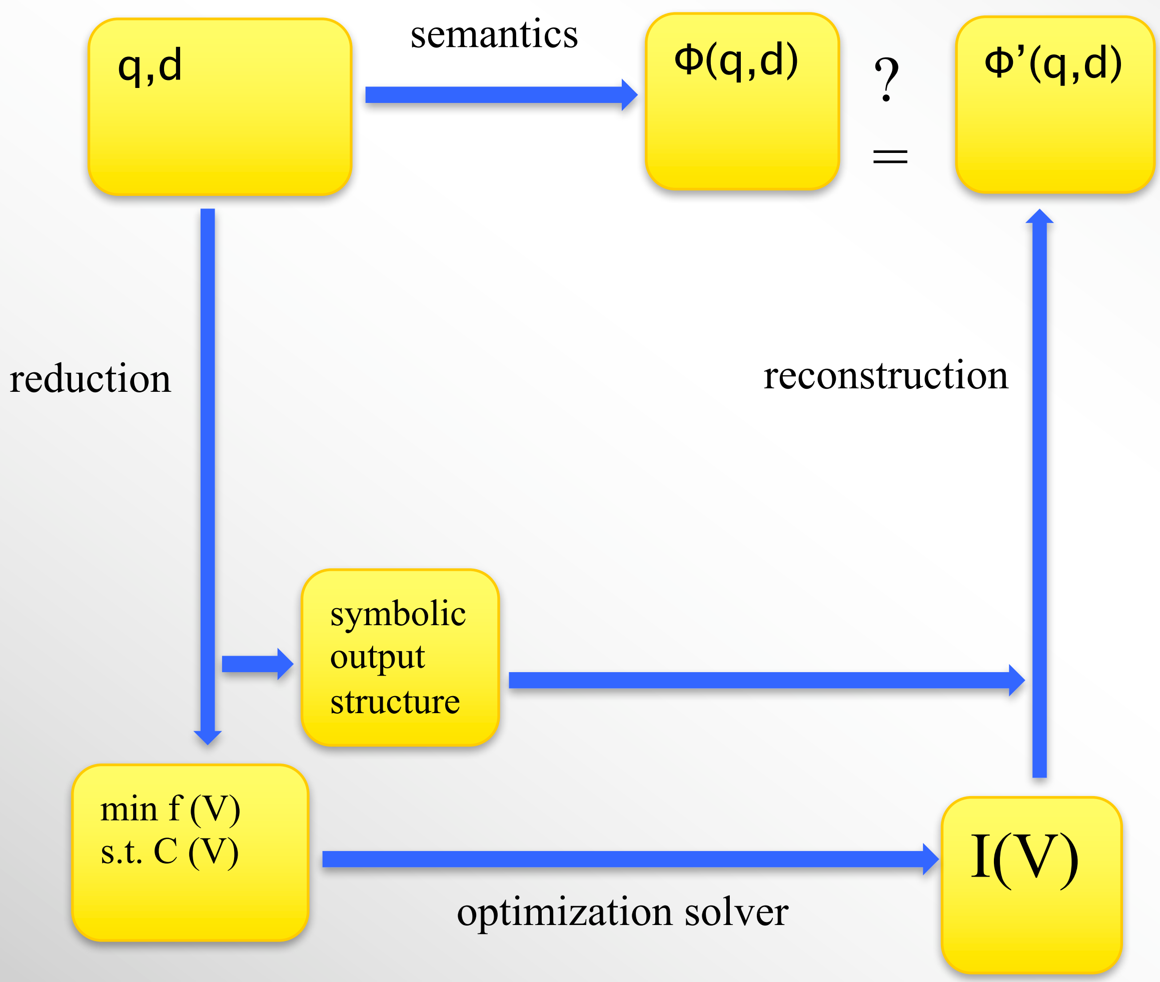
```
{
  "demand": {"chair": 16, "table": 4},
  "purchaseInfo": {
      "ppu": { "supplier1": {"chair": 50.00, "table": 110.00},
               "supplier2": {"chair": 60.00, "table": 100.00}
      },
      "available": { "supplier1": {"chair": 15, "table": 3},
                     "supplier2": {"chair": 20, "table": 2}
      },
      "qty": { "supplier1": {"chair": ???, "table": ??? },
               "supplier2": {"chair": ???, "table": ???}
      }
  }
}
```

```
{
  "cost": ???,
  "constraints": true
}
```

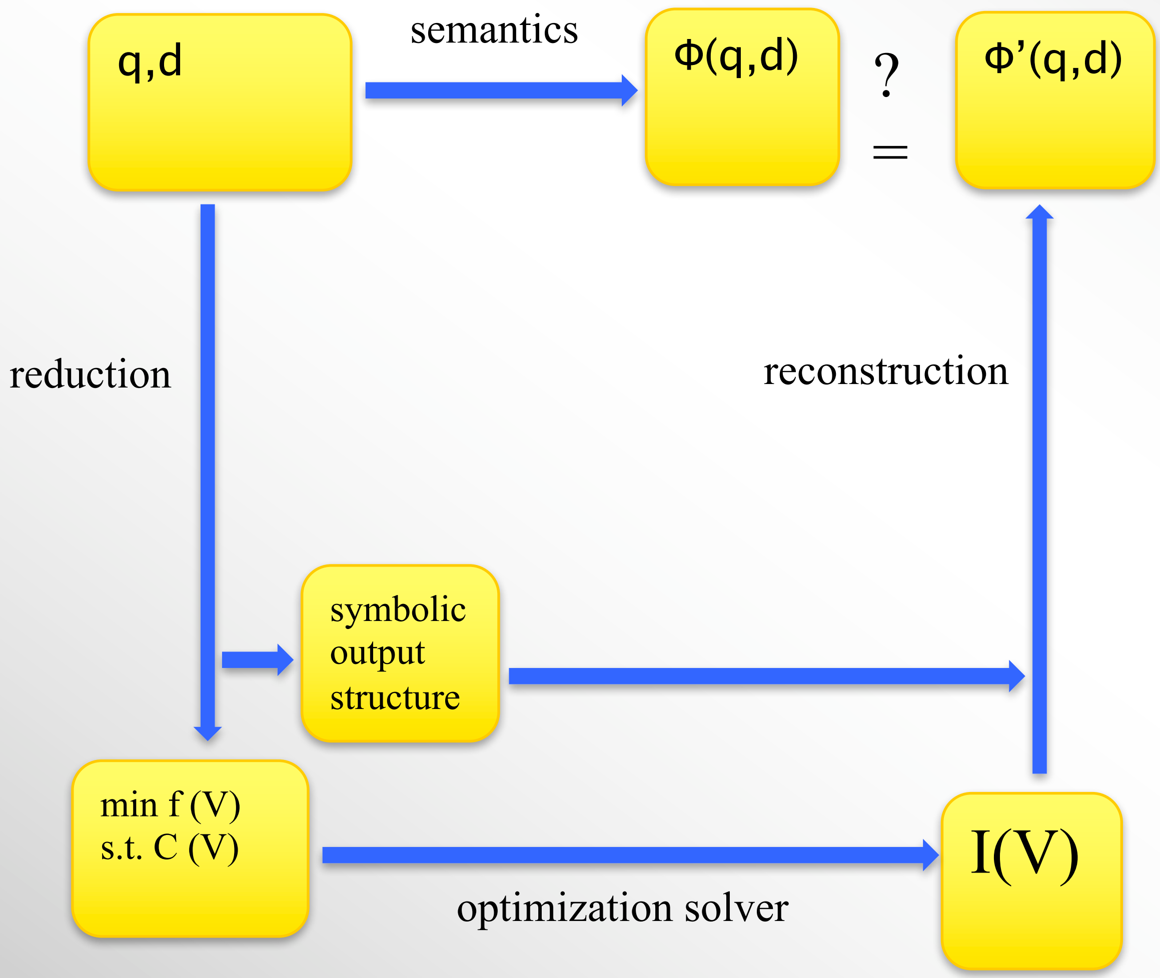

P: fixed params
V: control params
AM
M: metrics
C: constraints


AM
P: fixed params
V: ???
O: objective
Minimize/
Maximize
P: params
V: optimal control

Soundness and Completeness of Reduction



Soundness and Completeness of Reduction



Theorem:
The reduction procedure is

1. sound:
   $\Phi'(q,d) \subseteq \Phi(q,d)$

2. complete:
   $\Phi'(q,d) \supseteq \Phi(q,d)$

P: fixed params
V: control params

AM

M: metrics
C: constraints

AM

P: fixed params
V: ???

O: objective

Minimize/
Maximize

P: params
V: optimal control

AM

P: ???
V: ???

LS: training
set of input-
output pairs

Learn
Parameters

P: best fit params
V: ???

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P: fixed params
V: control params

Stochastic
AM

M: metrics
C: constraints

```
declare function local:stochProcurementPM($procurementInput){
  let $demand := $procurementInput.demand,,
      $suppliers := keys($procurementInput.purchaseInfo.ppu),
      $ppu := $procurementInput.purchaseInfo.ppu,
      $available := $procurementInput.purchaseInfo.available,
      $qty := $procurementInput.purchaseInfo.qty
  let $cost := sum ( for $s in $suppliers, $i in keys($qty($s)
                     let $stochPpu := $ppu($s)($i) + G(0.0,0.01*$ppu($s)($i))
                     return $stochPpu * $qty($s)($i)
               )
  let $availabilityConstraint := (
        every $s in $suppliers, $i in keys($qty($s))
        satisfies ( $qty($s)($i) <= $available($s)($i) )
      )
  let $supply := {|
        for $i in keys($demand)
        return {$i: sum ( for $s in $suppliers return $qty($s)($i) )}
      |}
  let $demandSatisfiedConstraint :=
        every $i in keys($demand)
        satisfies $supply($i) >= $demand($i) + G(0.0, 0.02 * $demand($i))
  let $feasibilityConstraint :=
        $availabilityConstraint and $demandSatisfiedConstraint
  return { cost: $cost, constraints: $feasibilityConstraint }
};
```

P: params
V: control vars

→ Stochastic AM →

M: metrics
C: constraints

AM

P: params
V: control vars

→ (stochastic) prediction →

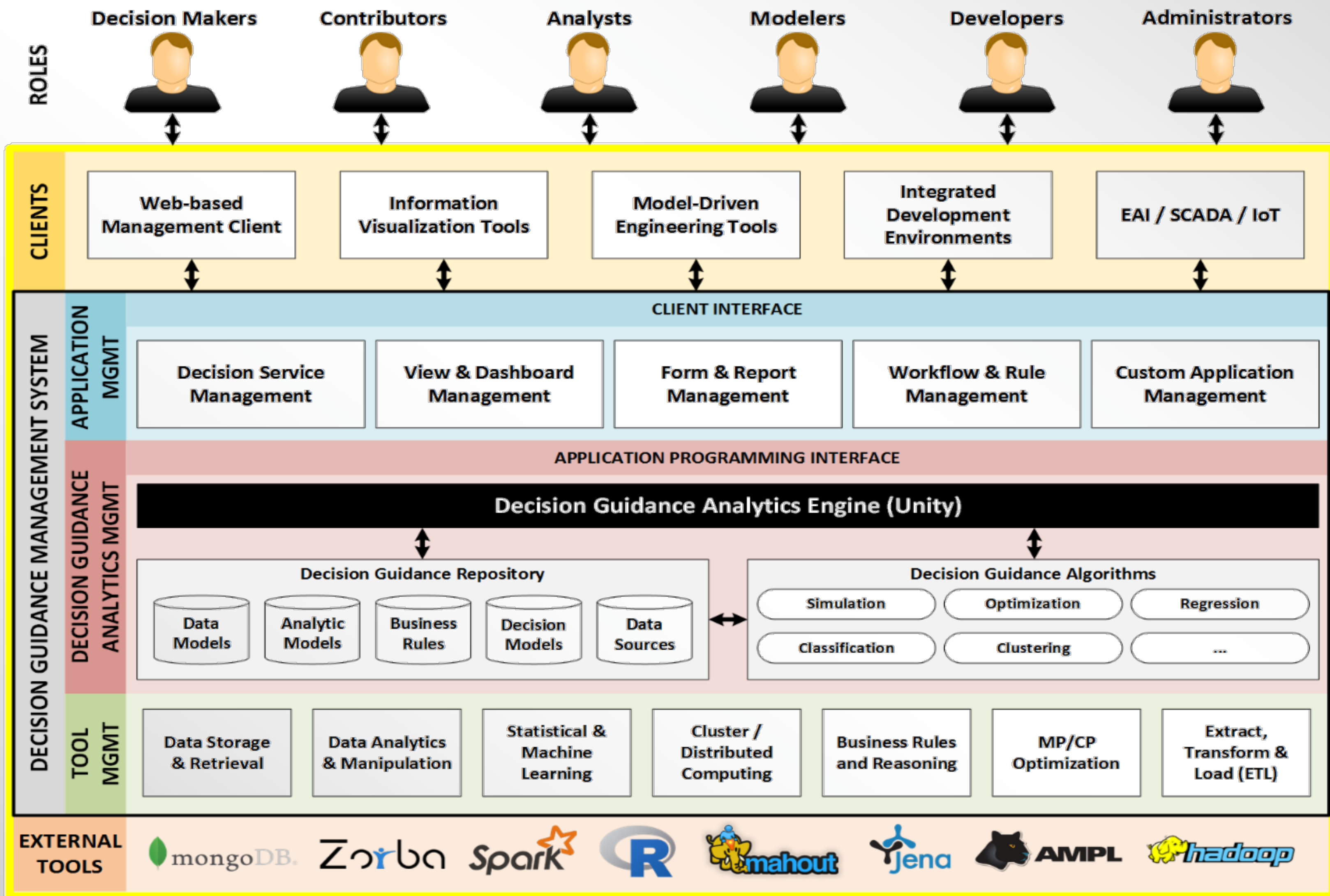
E(M): mean & std. dev. of metrics
P(C): prob. of constraint satisfaction


```
{ "cost": {"mean": 2120, "sigma": 8.76},
  "constraints": { "prob": 0.92},
}
```

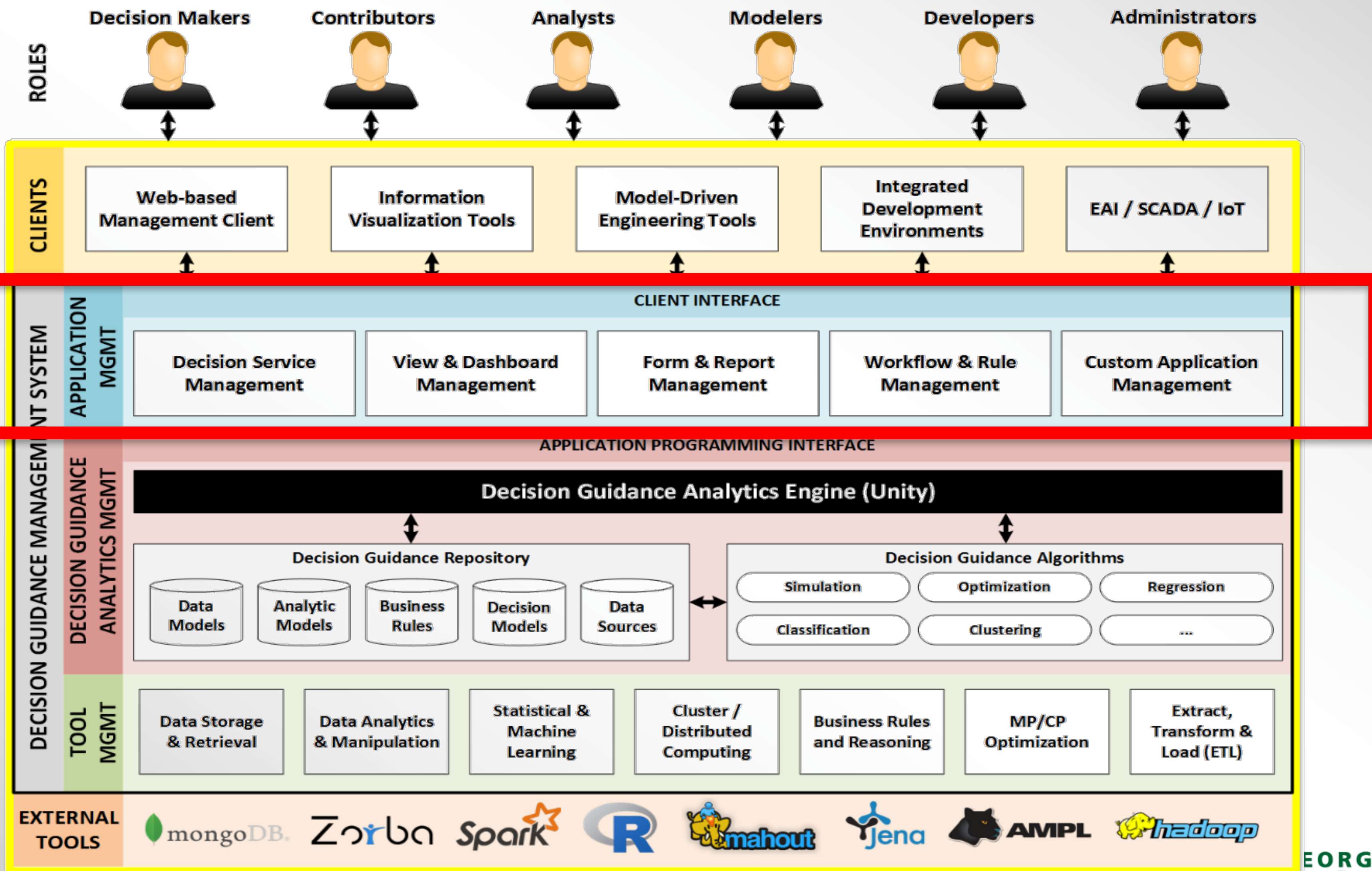
DGAL summary:

- Is based on KB of analytic (performance) models (AMs) that:
  - Express constraints and metrics of interest as a function of fixed & control parameters (of a process)
  - Are independent of analytical tasks & tools/algorithms
- Allows reuse of AMs as operands to diverse analytics operators (forming analytics algebra on AMs) :
  - Simulation
  - Prediction
  - Deterministic or stochastic optimization
  - Learning parameters of AM for regression or classification
  - …..
- Performs these operators/tasks by automatic reduction to specialized low-level models and algorithms, w/out the need to manually craft low-level models.
- Uses query / data manipulation language (JSONiq) over JSON data format to
  - Express AMs
  - Express analytics algebra operators / tasks

Unity DGMS architecture



Unity DGMS: application management layer



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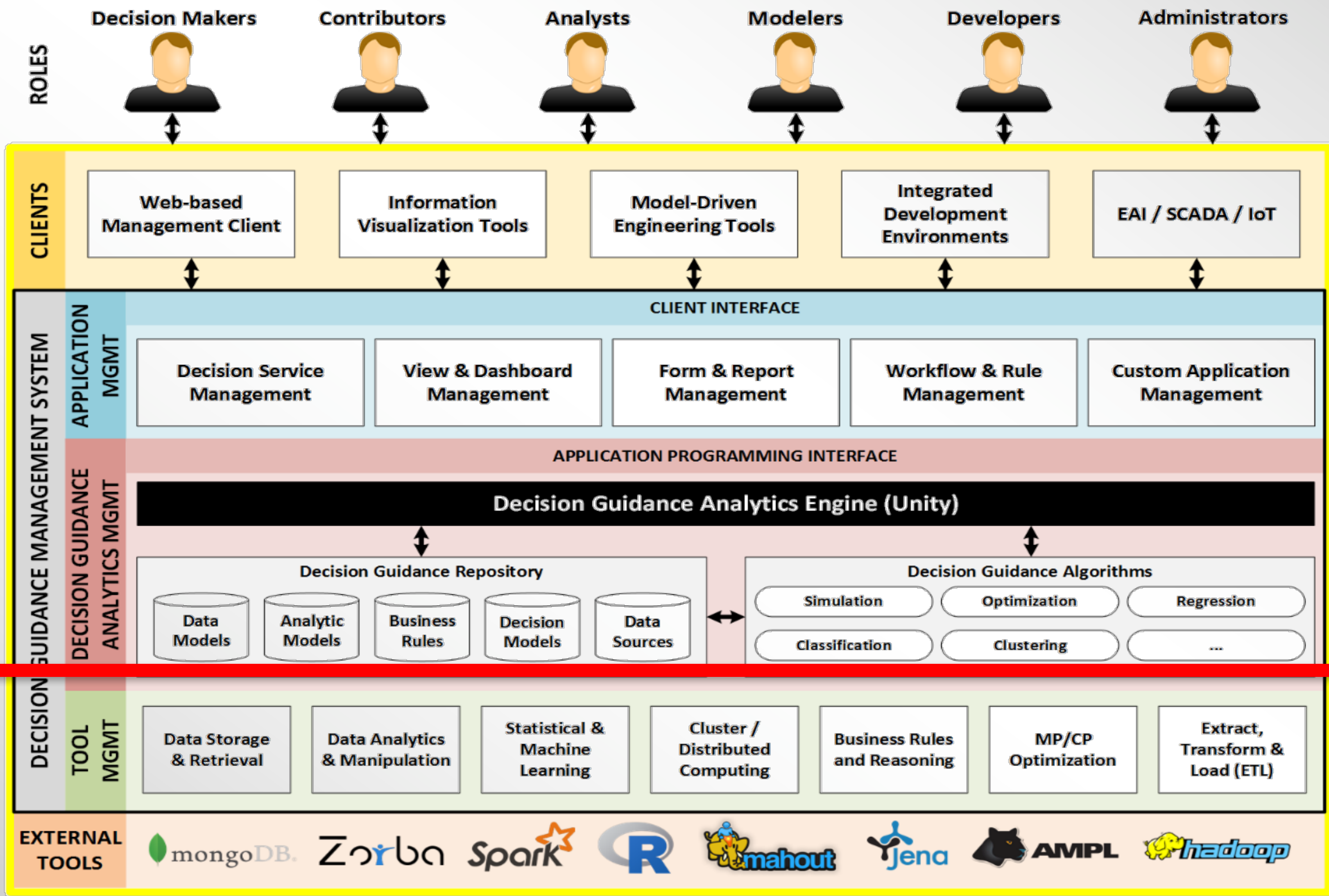
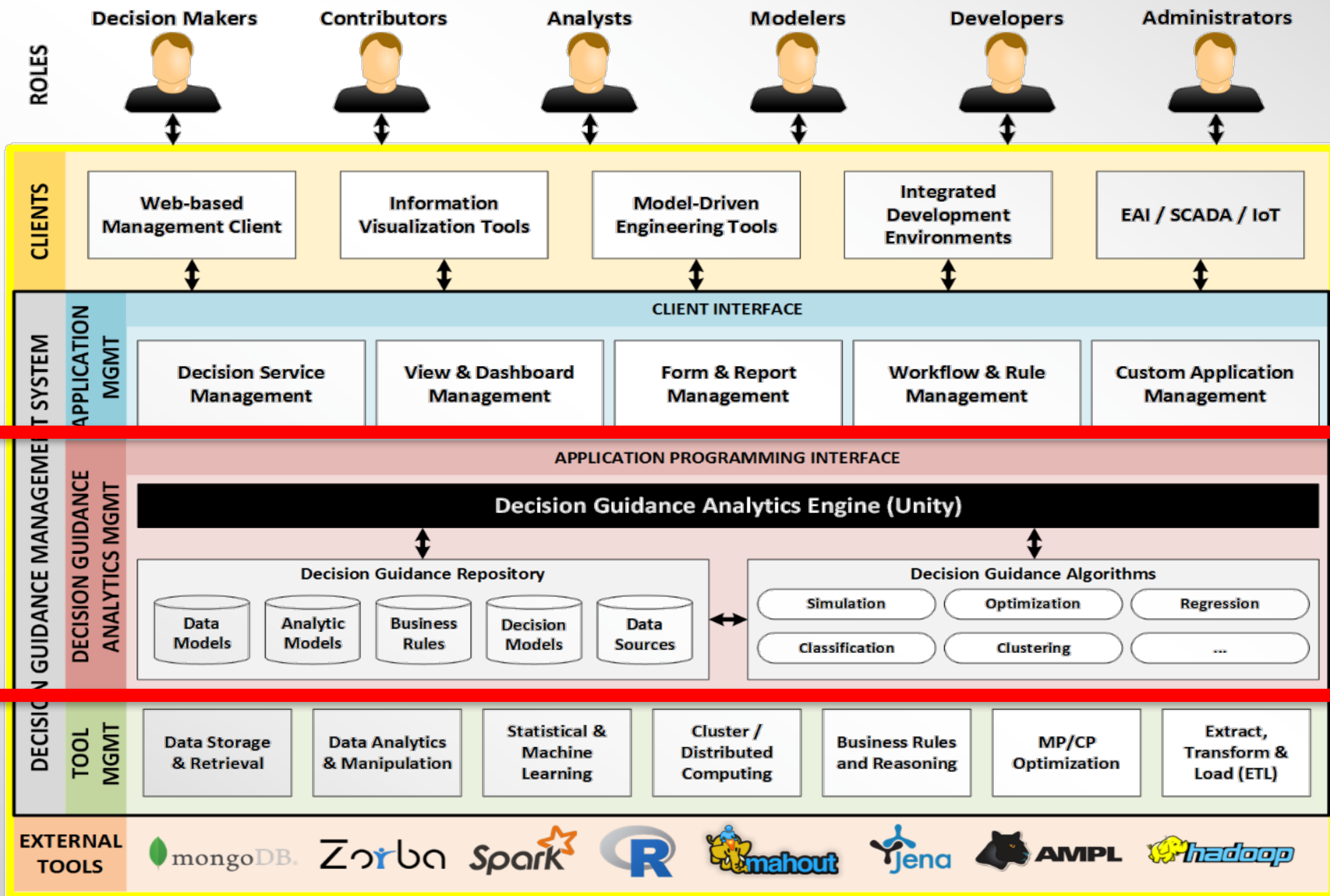
Unity DGMS: tool management layer



Unity DGMS: analytics management layer

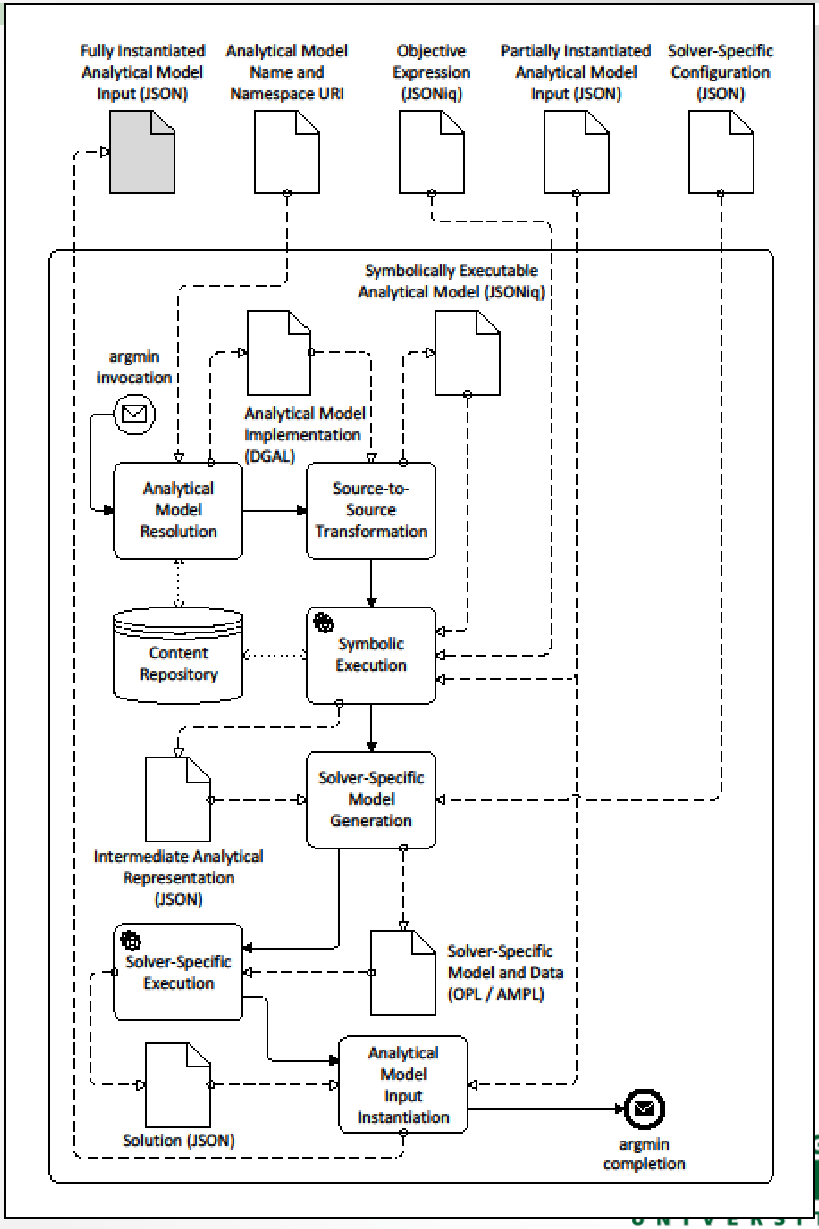


Compiling Optimization Queries

Six steps:

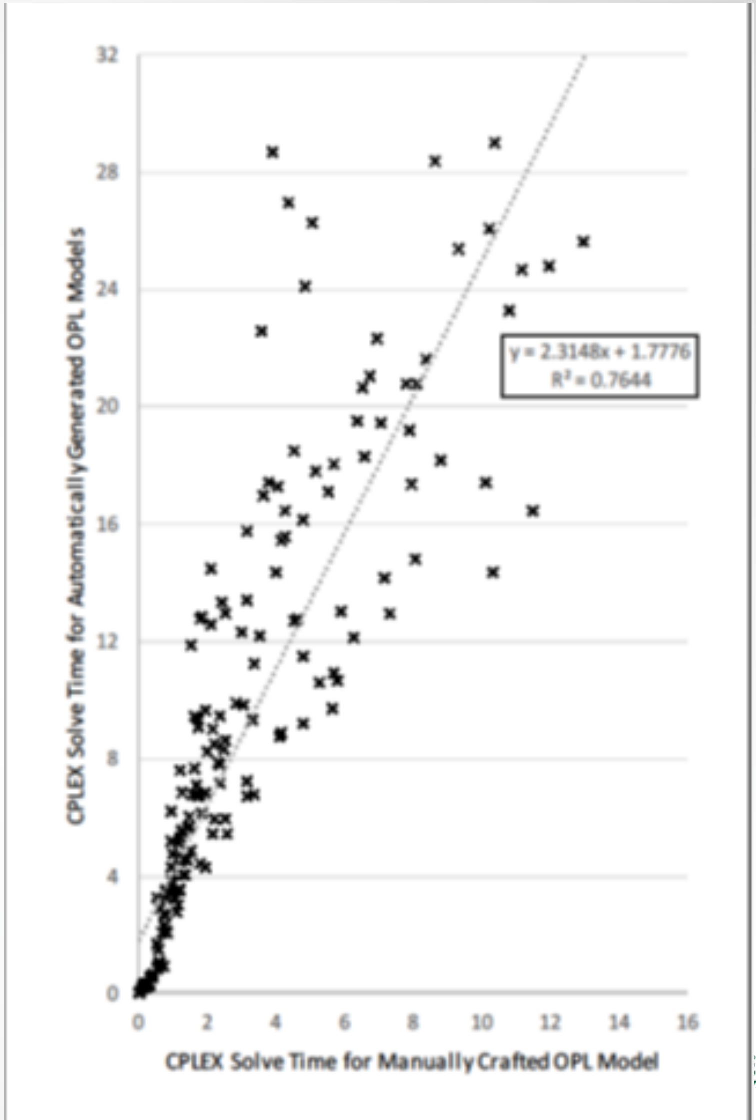
1. Reusable Analytic Model Resolution
2. Source-to-Source Transformation
3. Symbolic Execution
4. Target Model Generation
5. Target Solver Execution
6. Input Instantiation

Steps 1-3 & 6 (tasks) can be used to implement other DGAL operators: e.g. learn & predict



Preliminary performance evaluation

- **Hypothesis:** Execution time overhead of compiled reusable analytic models (into task- and tool-specific models) is within a constant factor of that of manually crafted ones
- **Method:** Compare execution times of compiled DGAL model versus manually crafted OPL model on randomized input pairs
- **Preliminary Results:** Compiled DGAL models are currently 2.3 times slower than manually crafted OPL models
- We are investigating techniques to improve performance of compiled models



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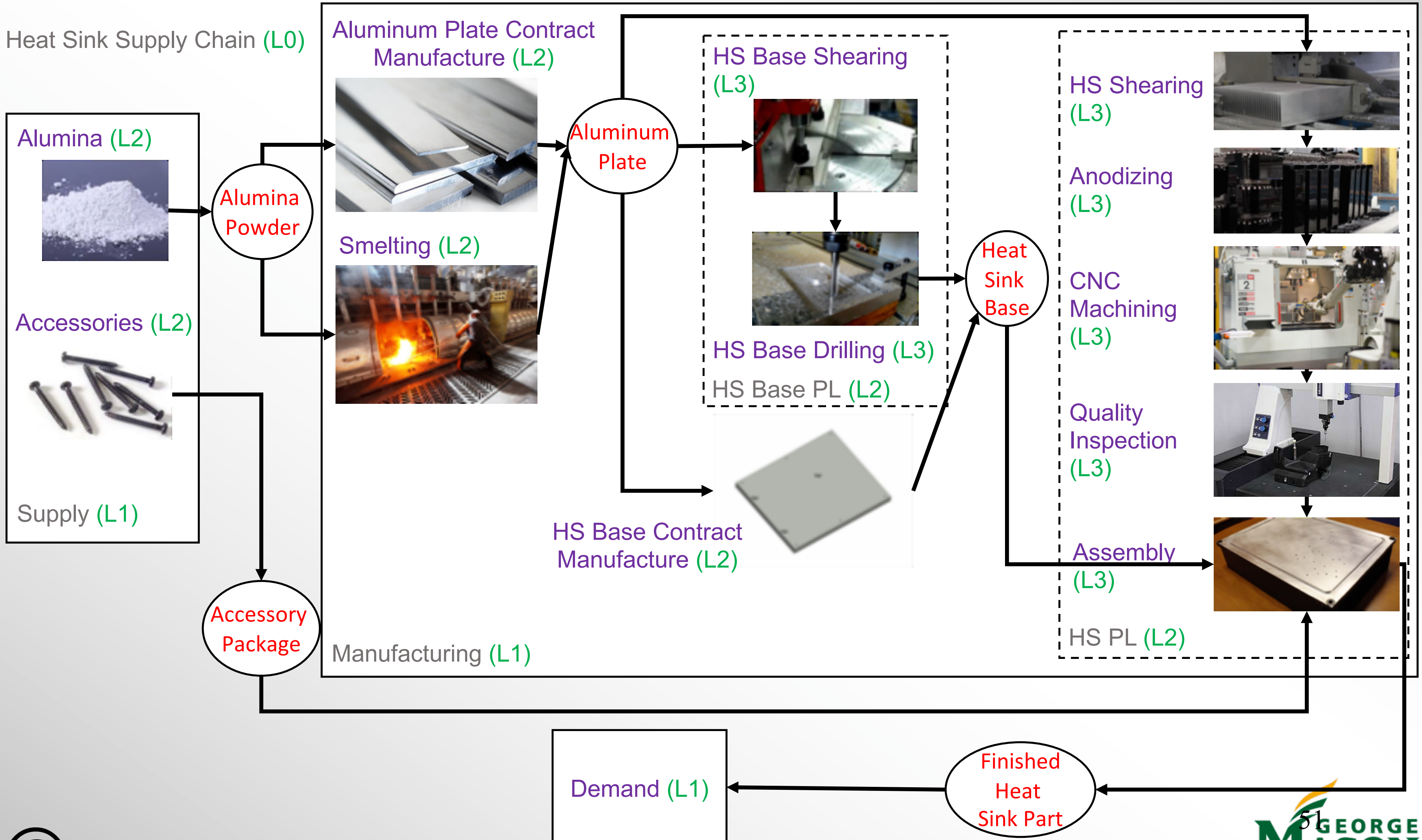
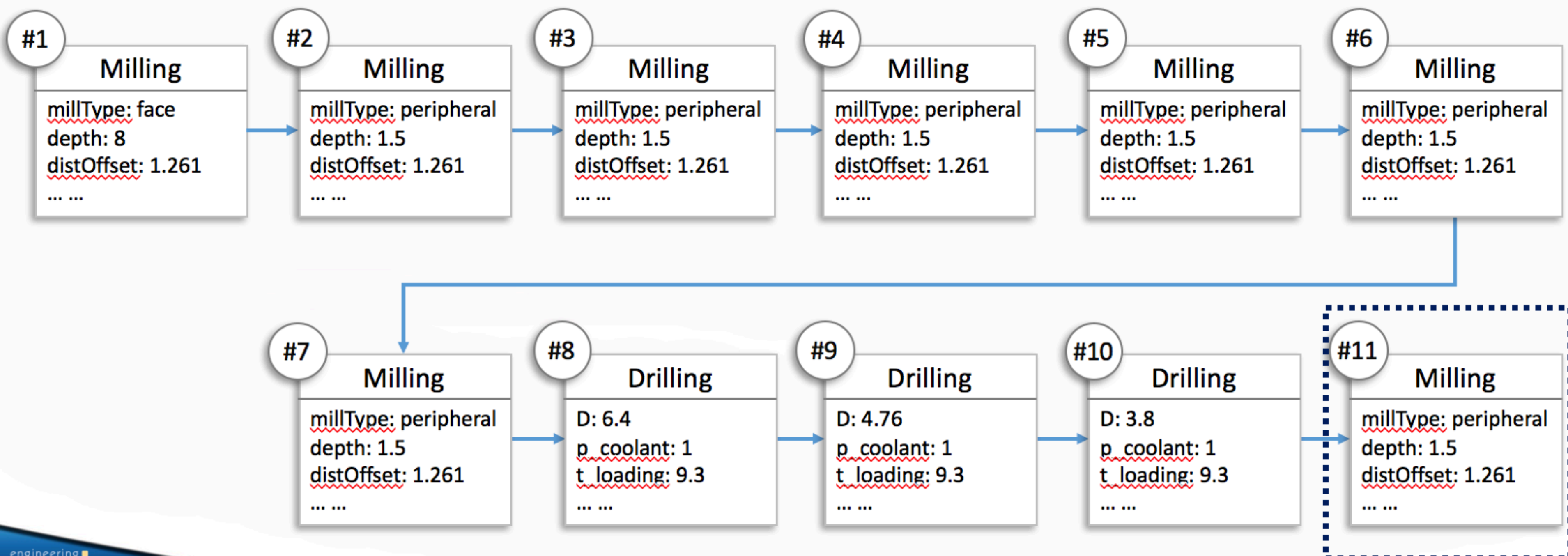
Heat sink (HS) assembly manufacturing & supply service network



Machining Sequence



Defining the nodes in the service network

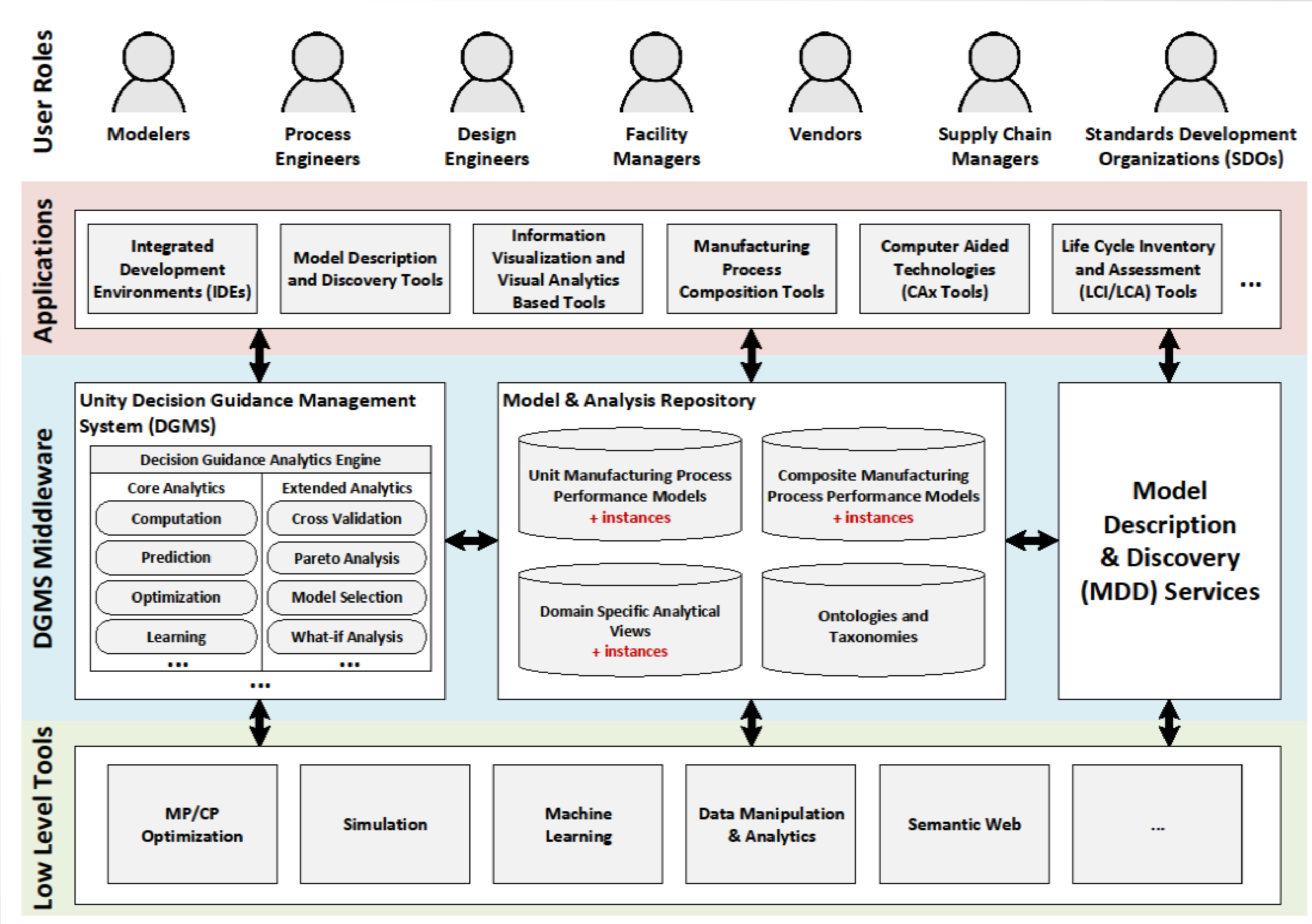
Vendor – organization that provides a finished product

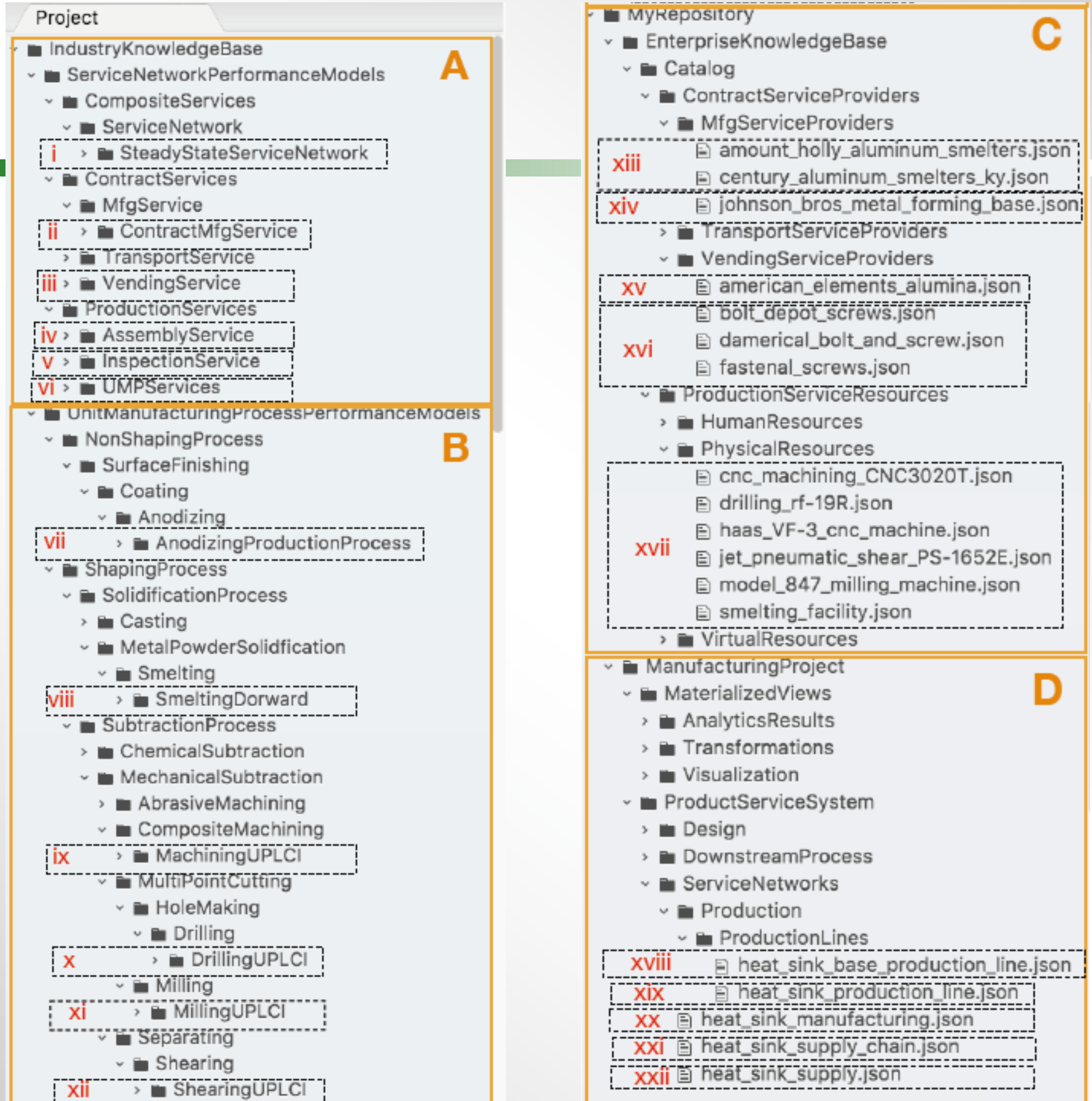
Contract Manufacturer – organization that provide a manufacturing service

Internal Manufacturer – internal activity controlled by OEM

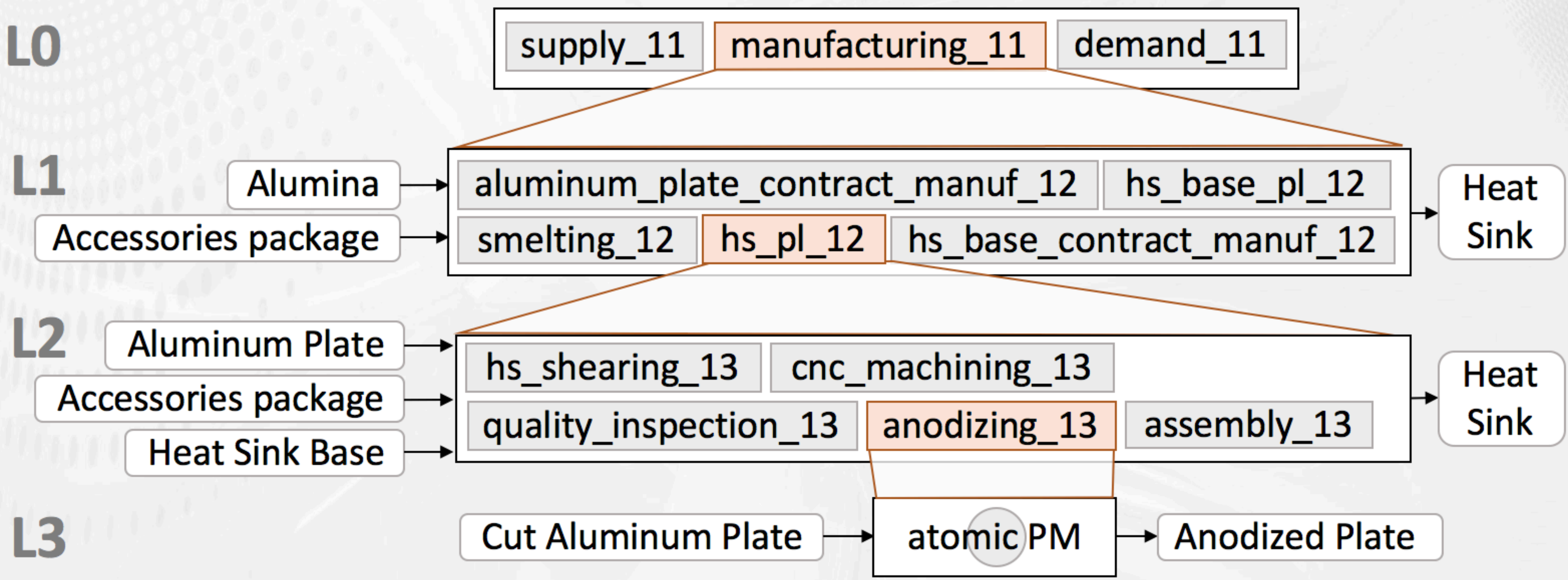
Production Line – a chain of internal manufacturer activities controlled by OEM

Architecture around NIST model repository




Project
A
IndustryKnowledgeBase
ServiceNetworkPerformanceModels
CompositeServices
ServiceNetwork
i
SteadyStateServiceNetwork
ContractServices
MfgService
ii
ContractMfgService
TransportService
iii
VendingService
ProductionServices
iv
AssemblyService
v
InspectionService
vi
UMPServices
B
UnitManufacturingProcessPerformanceModels
NonShapingProcess
SurfaceFinishing
Coating
Anodizing
vii
AnodizingProductionProcess
ShapingProcess
SolidificationProcess
Casting
MetalPowderSolidfication
Smelting
viii
SmeltingDorward
SubtractionProcess
ChemicalSubtraction
MechanicalSubtraction
AbrasiveMachining
CompositeMachining
ix
MachiningUPLCI
MultiPointCutting
HoleMaking
Drilling
x
DrillingUPLCI
Milling
xi
MillingUPLCI
Separating
Shearing
xii
ShearingUPLCI
C
MyRepository
EnterpriseKnowledgeBase
Catalog
ContractServiceProviders
MfgServiceProviders
xiii
amount_holly_aluminum_smelters.json
century_aluminum_smelters_ky.json
xiv
johnson_bros_metal_forming_base.json
TransportServiceProviders
VendingServiceProviders
xv
american_elements_alumina.json
xvi
bolt_depot_screws.json
damerical_bolt_and_screw.json
fastenal_screws.json
ProductionServiceResources
HumanResources
PhysicalResources
xvii
cnc_machining_CNC3020T.json
drilling_rf-19R.json
haas_VF-3_cnc_machine.json
jet_pneumatic_shear_PS-1652E.json
model_847_milling_machine.json
smelting_facility.json
VirtualResources
D
ManufacturingProject
MaterializedViews
AnalyticsResults
Transformations
Visualization
ProductServiceSystem
Design
DownstreamProcess
ServiceNetworks
Production
ProductionLines
xviii
heat_sink_base_production_line.json
xix
heat_sink_production_line.json
xx
heat_sink_manufacturing.json
xxi
heat_sink_supply_chain.json
xxii
heat_sink_supply.json

Composition of service network



```
"input": {
    "root": "heat_sink_part_service_network_root",
    "kb": {
        "heat_sink_part_service_network_root": {
            "analyticalModel": {
                "name": "computeMetrics",
                "ns": "http://repository.vsnet.gmu.edu/process/mfgServiceNetwork/composite/serviceNetwork/lib/service_network.jq"
            },
            "inputThru": {},
            "outputThru": {},
            "internalItems": ["Alumina","Accessories package","Heat Sink"],
            "subProcesses": ["supply_l1","manufacturing_l1","demand_l1"]
        },
        "manufacturing_l1": {
            "analyticalModel": {
                "name": "computeMetrics",
                "ns": "http://repository.vsnet.gmu.edu/process/mfgServiceNetwork/composite/serviceNetwork/lib/service_network.jq"},
            "inputThru": {
                "Alumina": {"v": {"decimal?": null}, "lb": 0},
                "Accessories package": {"v": {"decimal?": null}, "lb": 0}},
            "outputThru": {"Heat Sink": {"v": {"decimal?": null}, "lb": 0}},
            "internalItems": ["Alumina","Accessories package","Aluminum Plate","Heat Sink Base","Heat Sink"],
            "subProcesses": ["aluminum_plate_contract_manuf_l2", "smelting_l2",
                             "hs_base_pl_l2", "hs_base_contract_manuf_l2", "hs_pl_l2"]
        },
        "supply_l1": {
            "analyticalModel": {
                "name": "computeMetrics",
                "ns": "http://repository.vsnet.gmu.edu/process/mfgServiceNetwork/composite/serviceNetwork/lib/service_network.jq"},
            "inputThru": {},
            "outputThru": {"Alumina": {"v": {"decimal?": null}, "lb": 0},
                           "Accessories package": {"v": {"decimal?": null},"lb": 0}},
            "internalItems": ["Alumina", "Accessories package"],
            "subProcesses": ["alumina_vendor_l2", "accessories_vendor_l2" ]
        },
        "demand_l1": {
            "analyticalModel": {
                "name": "computeMetrics",
                "ns": "http://repository.vsnet.gmu.edu/process/mfgServiceNetwork/components/demand/lib/demand.jq"
            },
            "inputThru": {"Heat Sink": {"v": 2,"lb": 2 }},
            "outputThru": {},
            "co2perUnit": {},
            "ppu": {} ..............
```

Service network analytic model

supply_chain.jq

A

```
declare function ns:computeMetrics($input){
  let $rootProcess := $input.input.root
  let $output:= ns:computeSCmetrics($input.input.kb, $input.config,
                                     $rootProcess)
  return $output.$rootProcess
};
```

```
declare function ns:computeSCmetrics($stepsInputs, $config,
                                      $rootProcess){
  let
    $stepInput := $stepsInputs.$rootProcess,
    $analyticalModel := $stepInput.analyticalModel,
```

B

```
    $processMetrics := {},
    $processMetrics := {|
      if (not fn:matches($analyticalModel.ns,"supply_chain.jq")) then
        ns:evaluateAtomicProcesses({input: $stepInput, config: $config}
      else
```

C

```
        let $subProcessMetrics :=
            for $p in $stepInput.subProcesses[]
              return ns:computeSCmetrics
                ($stepsInputs, $config, $p),
```

D

```
          $metrics := ns:metricAggr(
           for $p in $stepInput.subProcesses[]
             return $subProcessMetrics.$p.metricValues),
          $inputThru := $stepInput.inputThru,
          $outputThru := $stepInput.outputThru,
```

E

```
          $subProcessConstraints :=
              every $p in $stepInput.subProcesses[] satisfies
                    $subProcessMetrics.$p.constraints,
```

F

```
          $boundConstraintsIT :=
             every $i in keys($inputThru) satisfies
                  cu:checkBounds($inputThru($i),$inputThru($i)("v")),
          $boundConstraintsOT :=
              every $o in keys($outputThru) satisfies
                  cu:checkBounds($outputThru($o),$outputThru($o)("v")),
```

supply_chain.jq

G

```
$processItems :=
  fn:distinct-values((
      keys($inputThru),keys($outputThru),
        (for $p in $stepInput.subProcesses[]
          return
            (keys($subProcessMetrics.$p.inputThru),
            keys($subProcessMetrics.$p.outputThru))
    ))),
    $zeroSumConstraints :=
      every $i in $processItems
        satisfies ( let
        $supply :=
          (if(fn:exists($inputThru($i)("v"))) then
            $inputThru($i)("v") else 0) +
            sum (for $p in $stepInput.subProcesses[]
              return $subProcessMetrics.$p.outputThru($i)("v"))
        $demand :=
          (if(fn:exists($outputThru($i)("v"))) then
           $outputThru($i)("v") else 0) +
           sum (for $p in $stepInput.subProcesses[]
             return $subProcessMetrics.$p.inputThru($i)("v"))
        return $supply ge $demand
      ),
```

H

```
      $constraints := $subProcessConstraints and
                       $boundConstraintsIT and
                       $boundConstraintsOT and
                       $zeroSumConstraints,
```

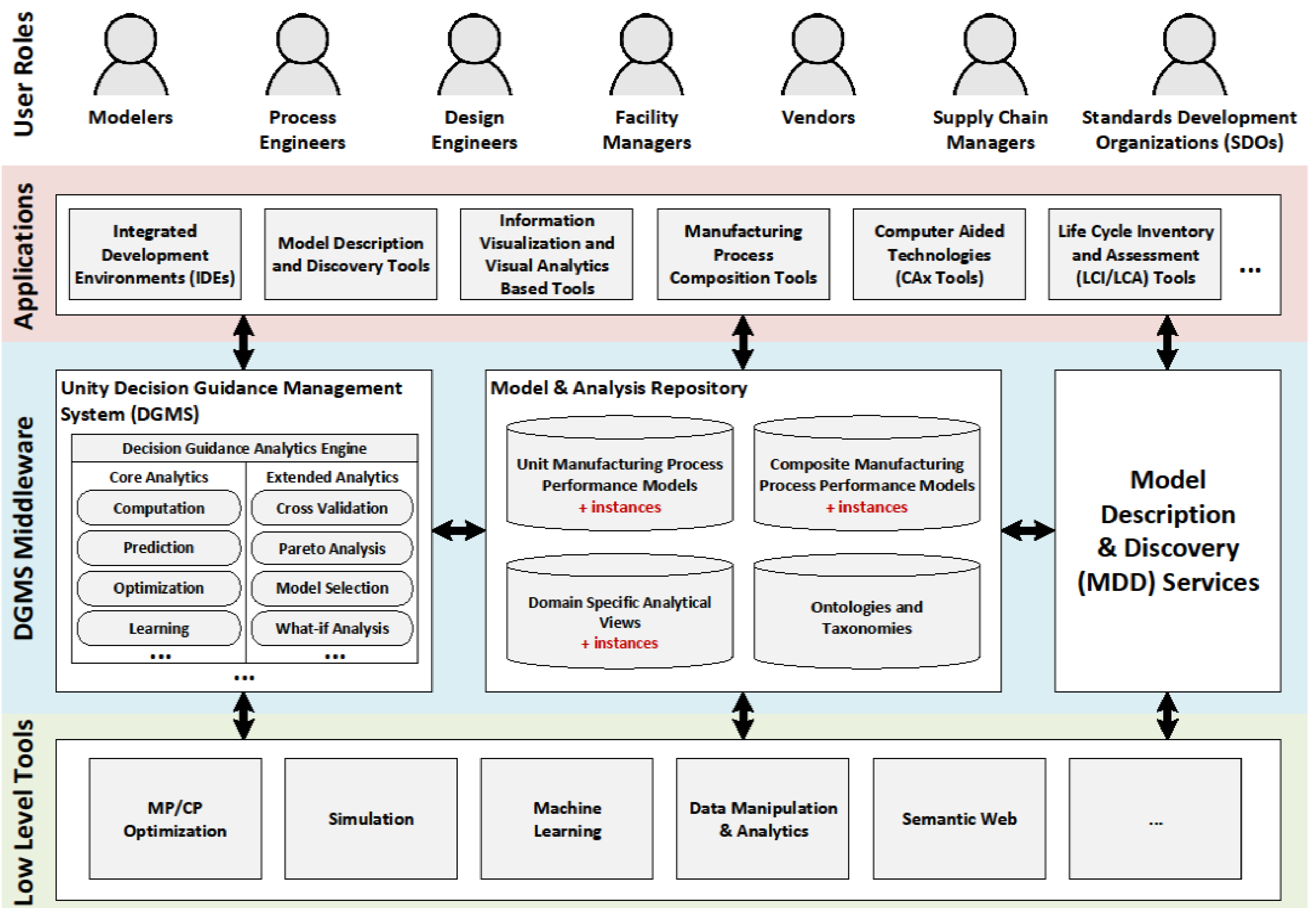
I

```
    $rootProcessMetrics := {
    analyticalModel:$stepInput.analyticalModel,
    inputThru:$inputThru,
    outputThru:$outputThru,
    metricValues: $metrics,
    constraints: $constraints
  }
```

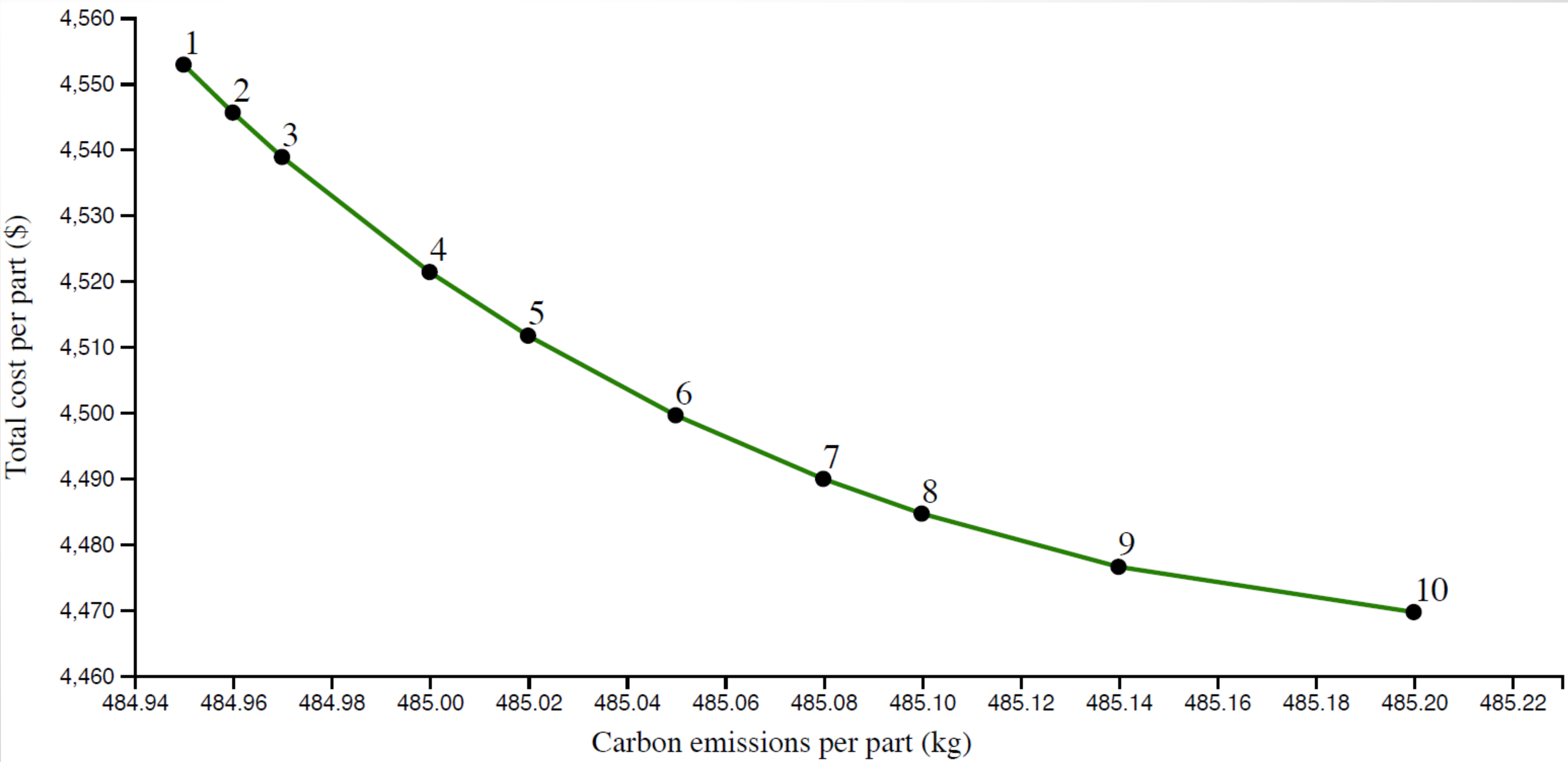
Service network analytic model (SV-AM): key steps

1. If Service atomic, invoke its corresponding AM
2. Else (* if service has sub-services *)
   a. Recursively invoke SV-AM for every sub-service
   b. Aggregate metrics
   c. Evaluate constraints, which comprise of:
      i. All sub-service constraints
      ii. Bounds on Control (decision) variables
      iii. Zero-sum flow constraints
3. Return output that comprise of:
   a. Aggregated metrics
   b. Evaluated constraints
   c. For every descendent sub-service, its aggregated metrics & evaluated constraints

Architecture around NIST model repository



Example: Pareto front computation



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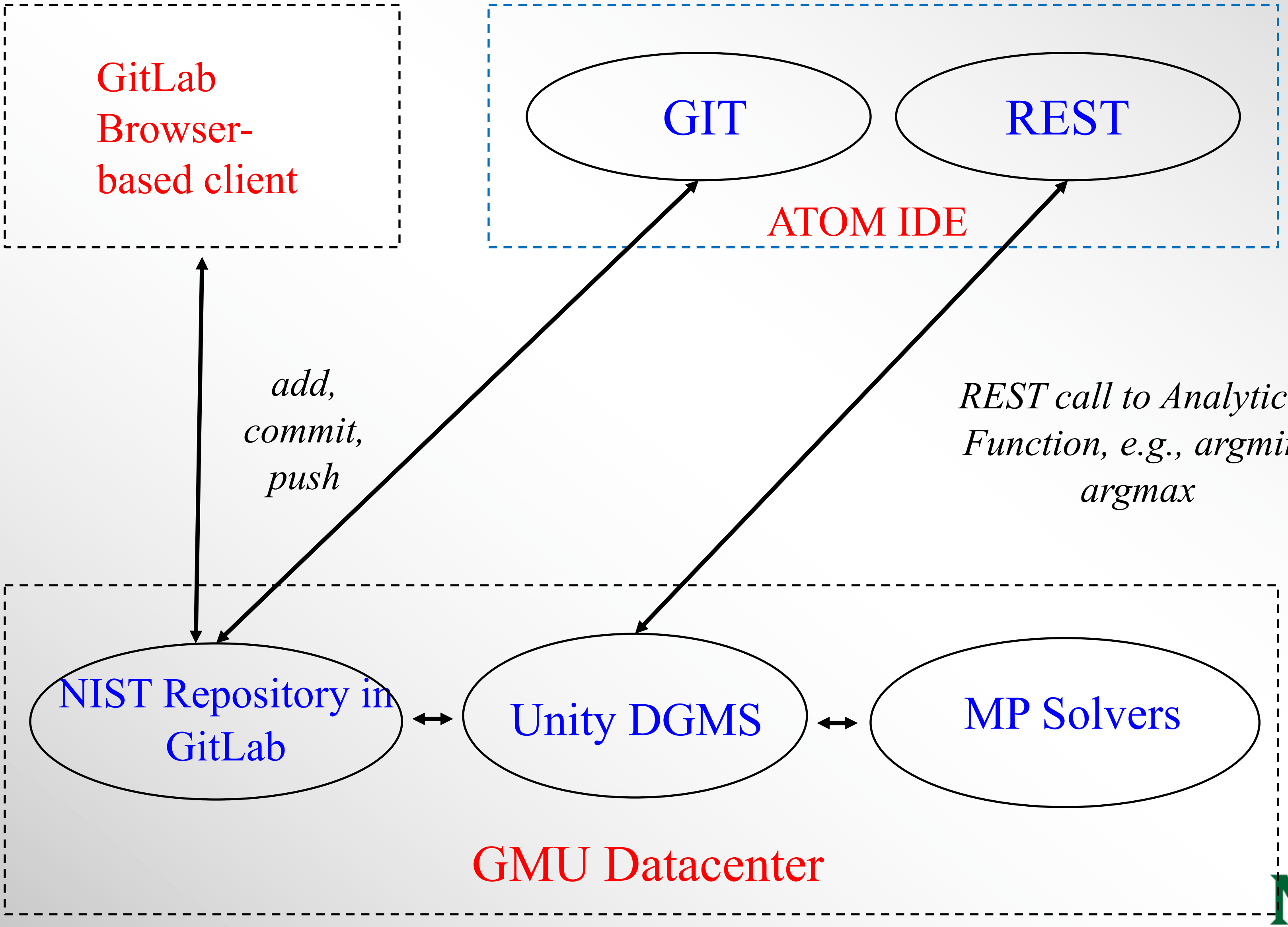
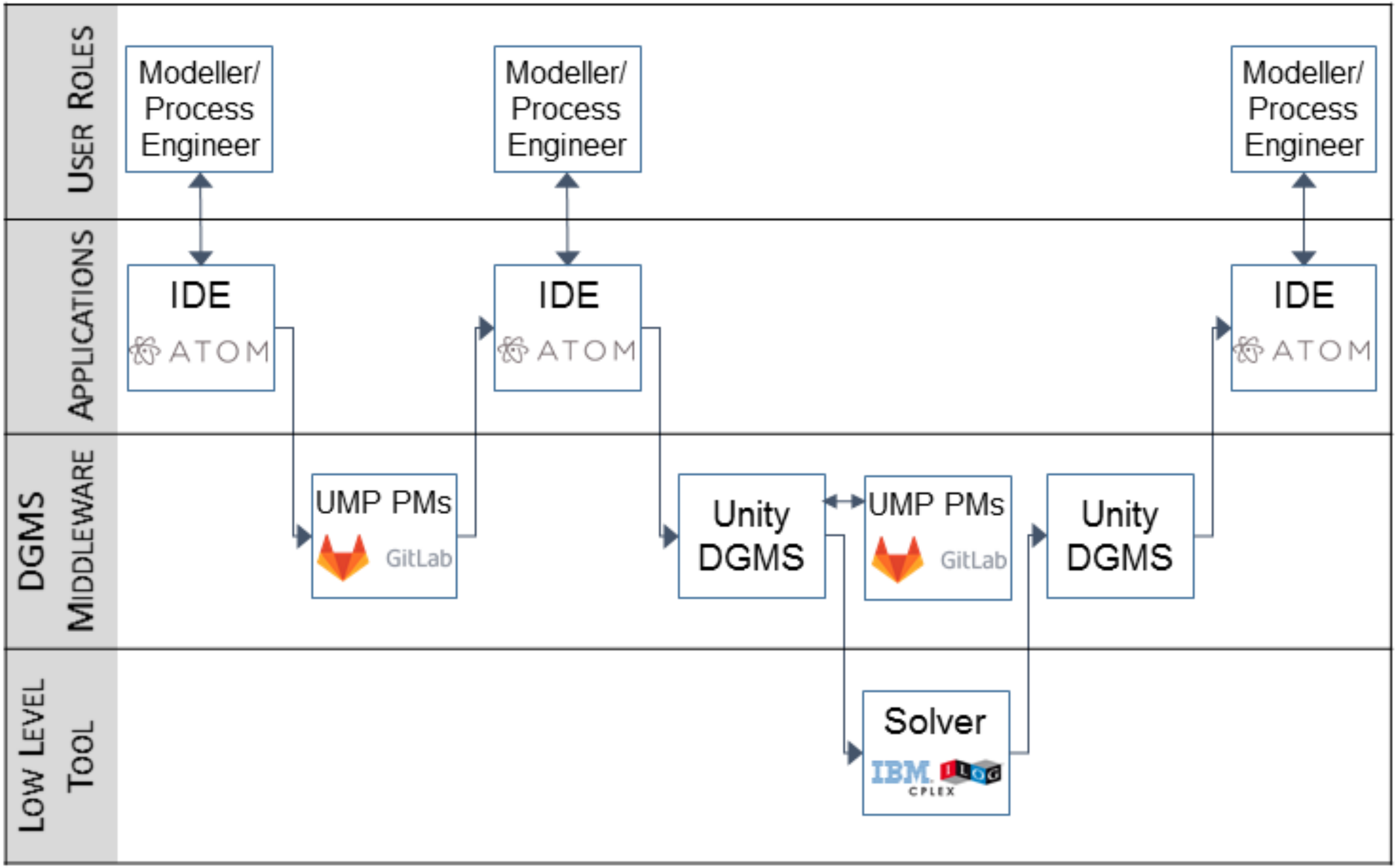
Initial deployment architecture



System workflow



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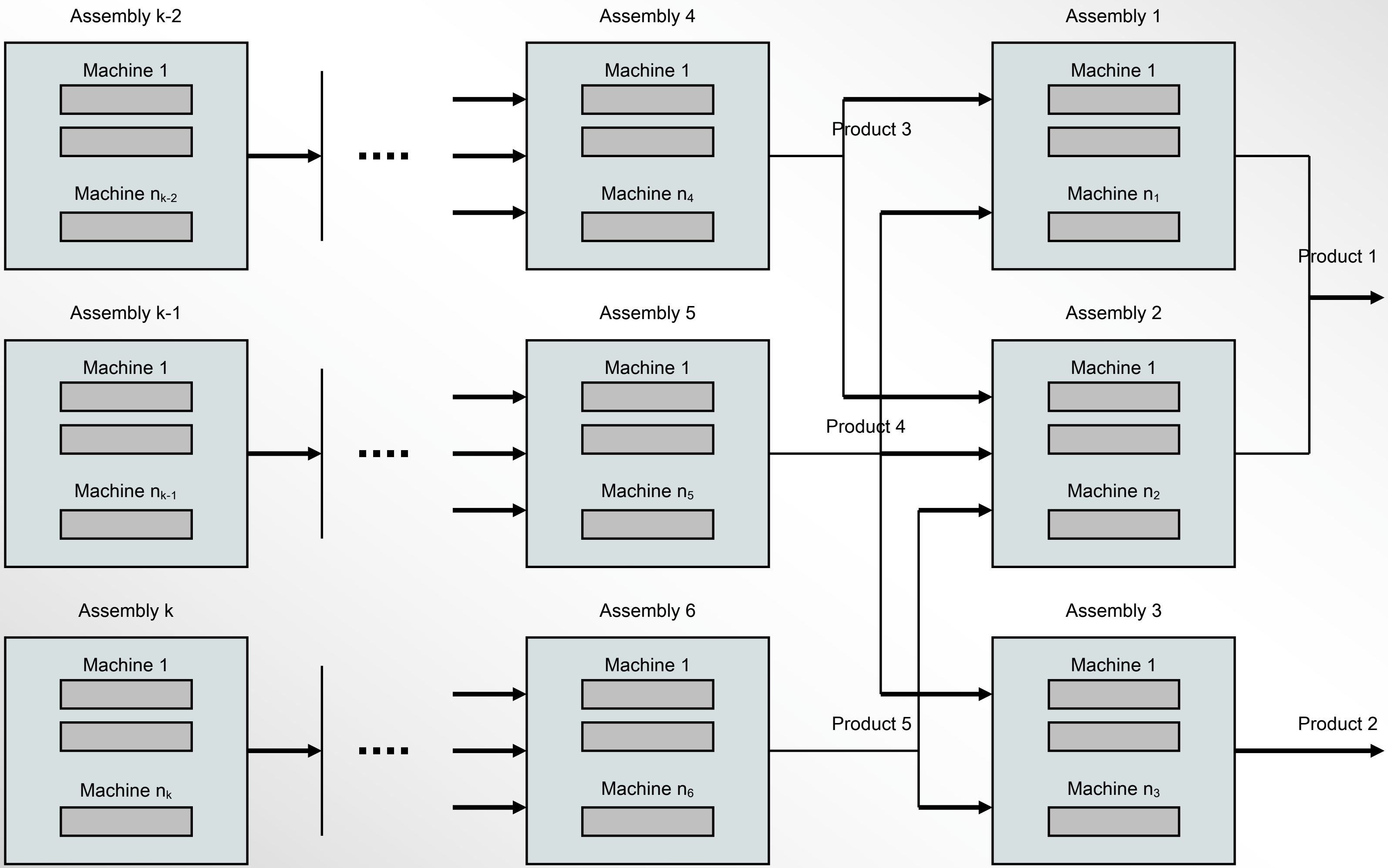
Problem: cost minimization in multistage production network



Multi-stage production optimization problem:

- Decision variables:
  - For every machine: *ON* flag & *thru* (or low level controls)
  - *thru* of all flows
- Constraints:
  - For every machine:
    - *cost* as a function of *thru*
    - *thru* bounds
    - input material *qty* as a function of output *qty*
  - Zero-sum flow
  - Demand satisfaction
- Objective: minimize total cost

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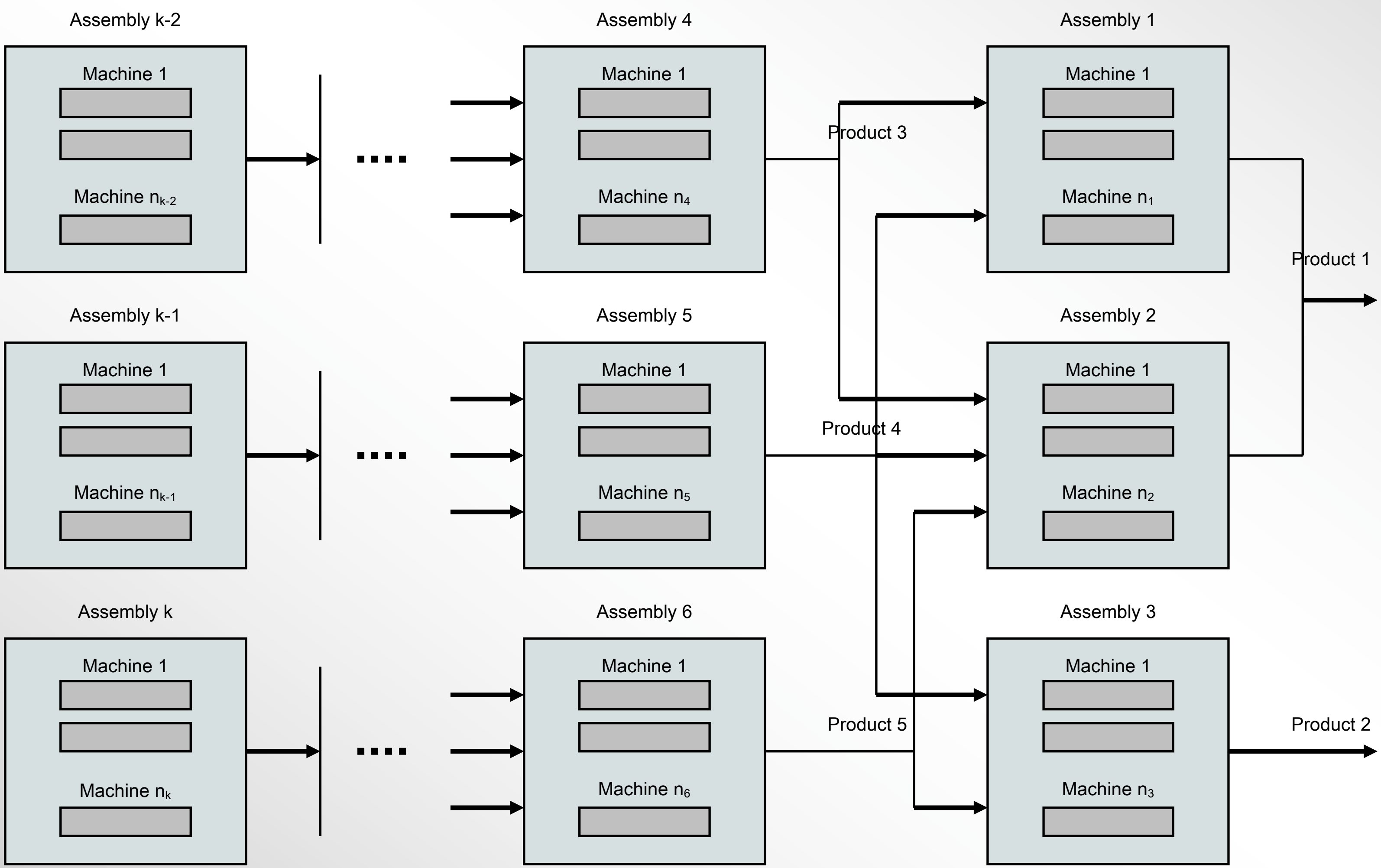
MP Problem Formulation

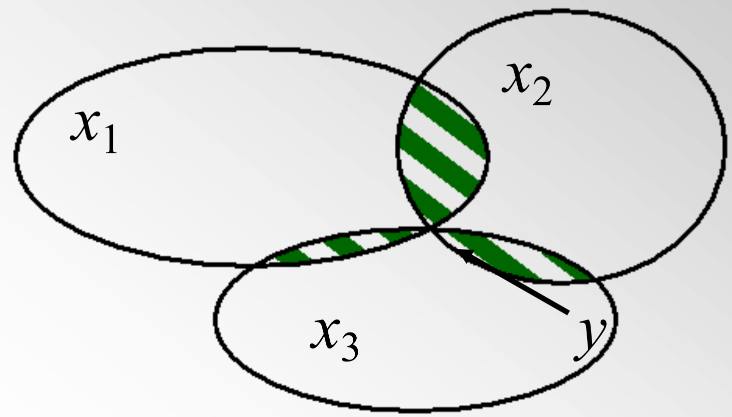
```
MINIMIZE total_cost:
    SUM{m IN Machines} Cost[m];

SUBJECT TO
    machine_operation {m IN Machines}:
        MinQty[m] <= Qty[m] <= MaxQty[m];
    machine_cost {m IN Machines}:
        Active[m] = 0 ==> Cost[m] = 0
            ELSE Cost[m] = c3[m]*Qty[m]^3 + c2[m]*Qty[m]^2 + c1[m]*Qty[m] + c0[m];
    machine_production {m IN Machines}:
        Active[m] = 0 ==> MachQty[m] = 0
            ELSE MachQty[m] = Qty[m];

assembly_production {a IN Assemblies}:
        AsmQty[a] = SUM{m IN Machines} Production[a,m] * MachQty[m];
    product_production {p IN Products}:
        Produced[p] = SUM{a IN Assemblies} Output[p,a] * AsmQty[a];
    demand_vs_produced {p IN Products}:
        Producted[p] >= Demand[p] +
            SUM{a IN Assemblies} Resources[a,p] * AsmQty[a];
```

Intuition behind approximations and problem decomposition



Principles of Preprocessing & Decomposition

$x = y \cup x_1 \cup \ldots \cup x_n$



$\min f(x)$ s.t. $C(x)$

of the form:

$$\min \; f_1(x_1,y) + \ldots + f_n(x_n,y) \qquad \text{(I)}$$
$$\text{s.t. } C_1(x_1,y) \wedge \ldots \wedge C_n(x_n,y) \wedge C_0(y)$$

Problem: $x_1, \ldots, x_n$ may involve many finite domain or binary variables

Decomposition Key Idea

Find optimal values for interface variables *y* and fix to decompose problem.

Define: $F_1(y) = \min_{x_1} f_1(y, x_1)$ $\quad$ $K_1(y) = (\exists\, x_1)\ C_1(y, x_1)$

$\vdots \qquad \vdots \qquad\qquad \vdots \qquad \vdots$

$F_n(y) = \min_{x_n} f_n(y, x_n)$ $\quad$ $K_n(y) = (\exists\, x_n)\ C_n(y, x_n)$

Step 1

Solve: $\min F_1(y) + \ldots + F_n(y)$ (II)

s.t. $K_1(y) \wedge \ldots \wedge K_n(y) \wedge C_0(y)$

Claim:

- A solution to (II) is a partial solution to the original problem, i.e., if y^* is a solution to (II) then there exists a solution $(y^*, x_1^*, \ldots, x_n^*)$ to (I)
- A solution to the original problem (I) gives a solution to (II), i.e., if $(y^*, x_1^*, \ldots, x_n^*)$ is a solution to (I) then y^* is a solution to (II)

Decomposition Key Idea Cont.

Step 2

Solve: $\min_{x_1} f_1(y^*, x_1)$ s.t. $C_1(y^*, x_1)$ (1)

$\vdots$ $\vdots$ $\vdots$

$\min_{x_n} f_n(y^*, x_n)$ s.t. $C_n(y^*, x_n)$ (n)

Claim: Step 1 and Step 2 give a solution to the original problem, i.e.,

if x_1^* is a solution to (1), then $(y^*, x_1^*, \ldots, x_n^*)$ is a solution to (I)

$\vdots$ $\vdots$

x_n^* is a solution to (n),

Essentially, Step 1 "decomposes" a (large) combinatorial problem into n (smaller) combinatorial problems which areeasier to solve.

Problem: $F_1(y), \ldots, F_n(y)$ and $K_1(y), \ldots, K_n(y)$ may not have an analytical form to solve (II) using existing solver technology (e.g., LP, MILP, QP, NLP, etc.)

Approach

Approximate $F_1, \ldots, F_n$ and $K_1, \ldots, K_n$ using smooth functions for which we can use efficient solver techniques (LP, NLP, etc.).

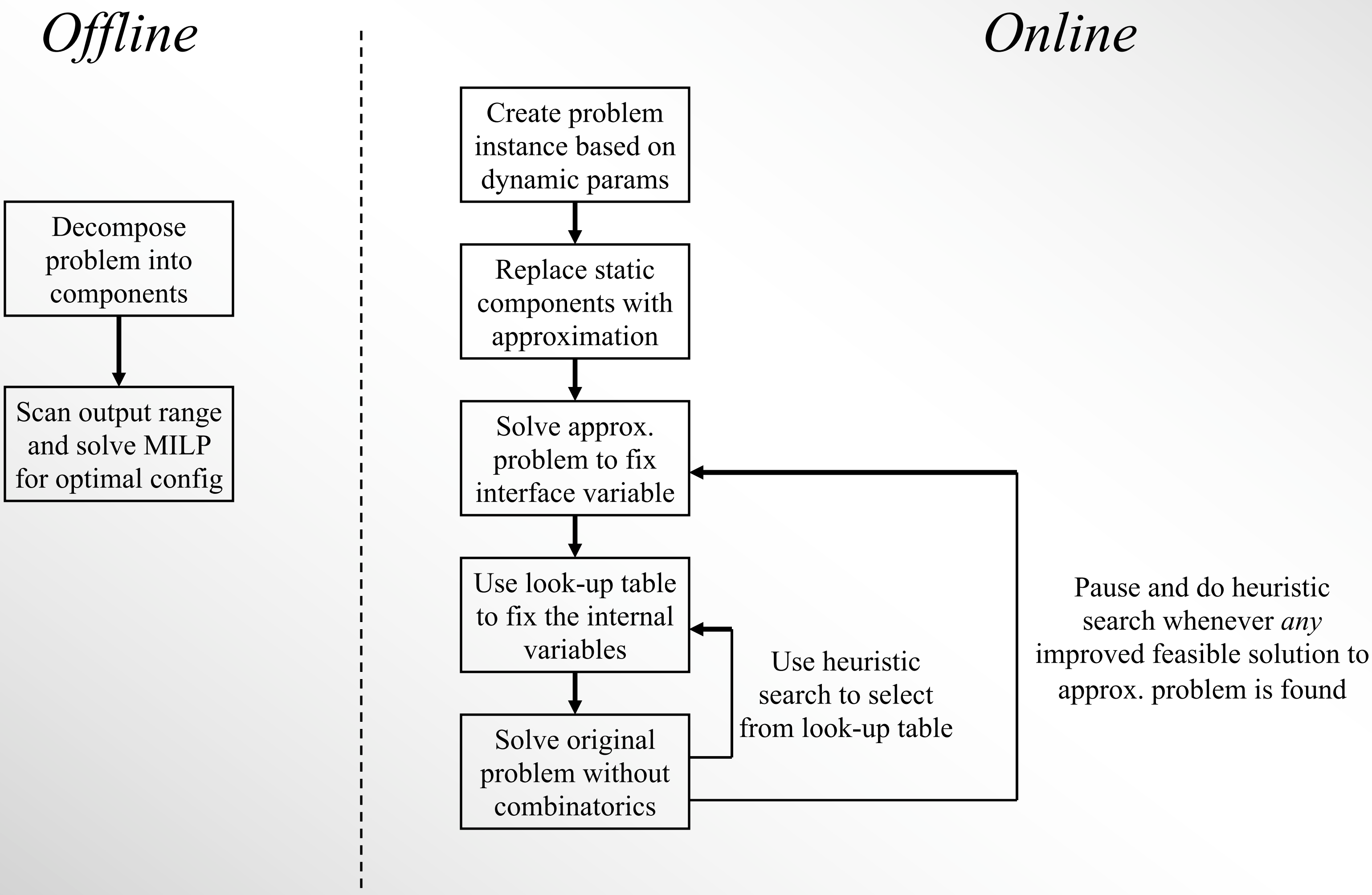
Preprocessing:

1. Partition input space y, solve sub-problem exactly to build lookup table
2. Regression analysis to learning smooth approximation of $F_1, \ldots, F_n, K_1, \ldots, K_n$

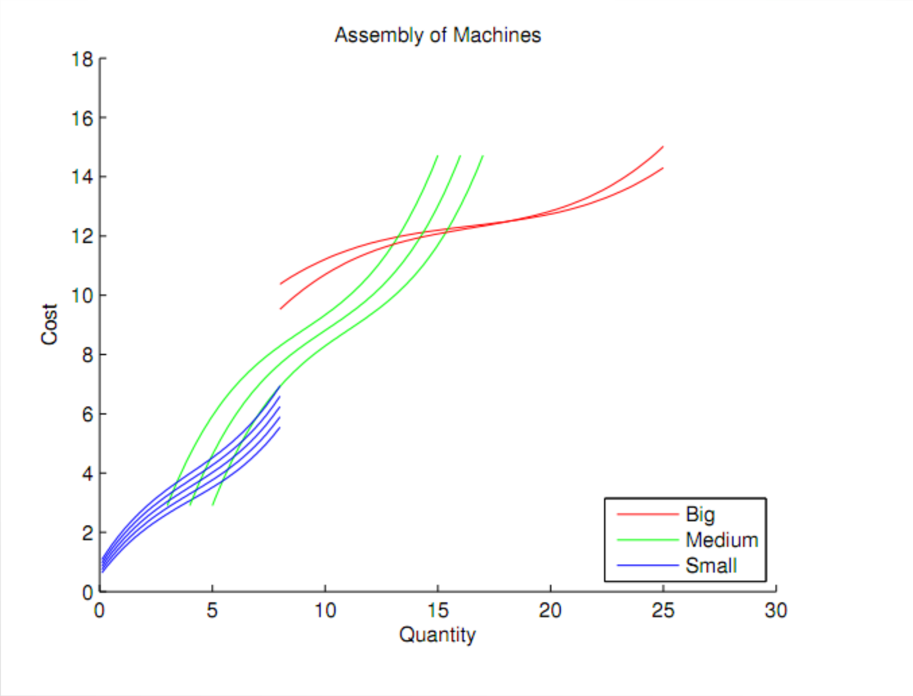
On-line:

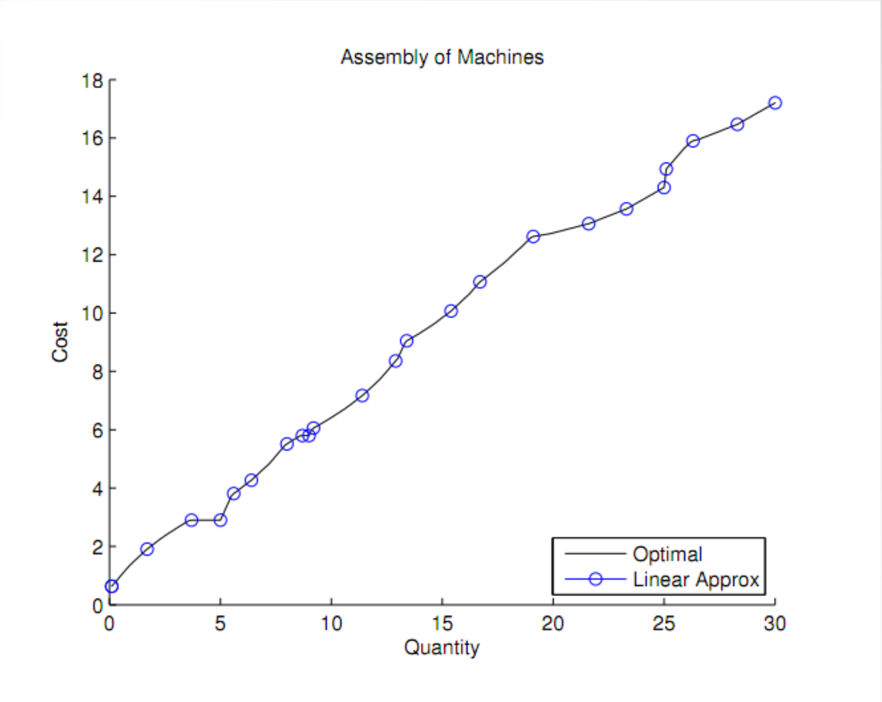
1. Solve (II) for y^* using approximation for $F_1, \ldots, F_n$ and $K_1 \ldots, K_n$
2. Solve (1) … (n) based on y^*, find finite domain and binary variables $x_1, \ldots, x_n$
3. Solve original problem (I), where combinatorial part of the problem is fixed using the solution from Step 2

Online Decomposition Algorithm (ODA)

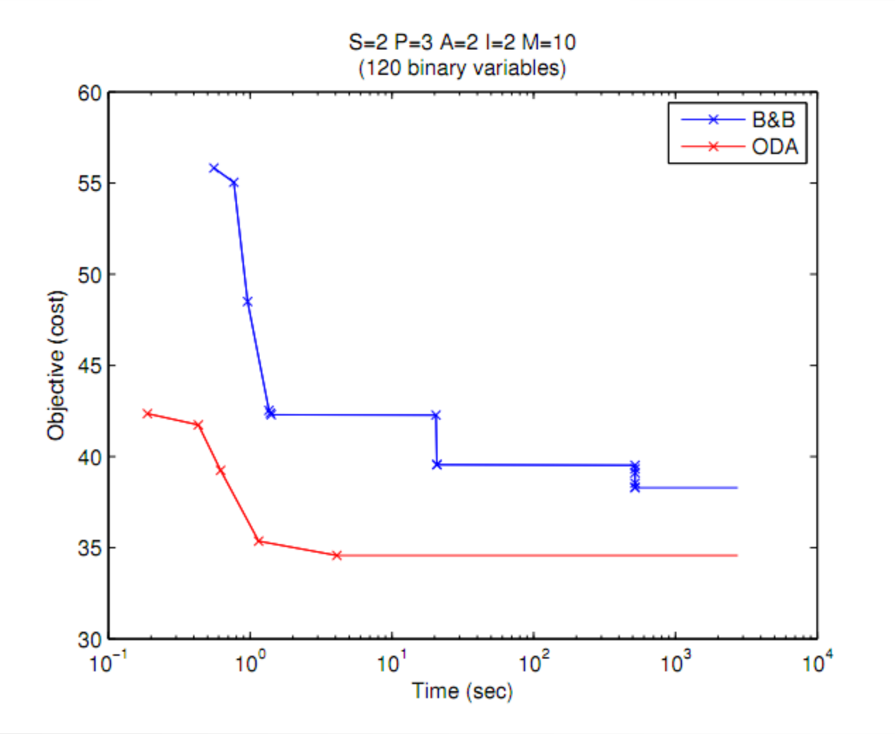


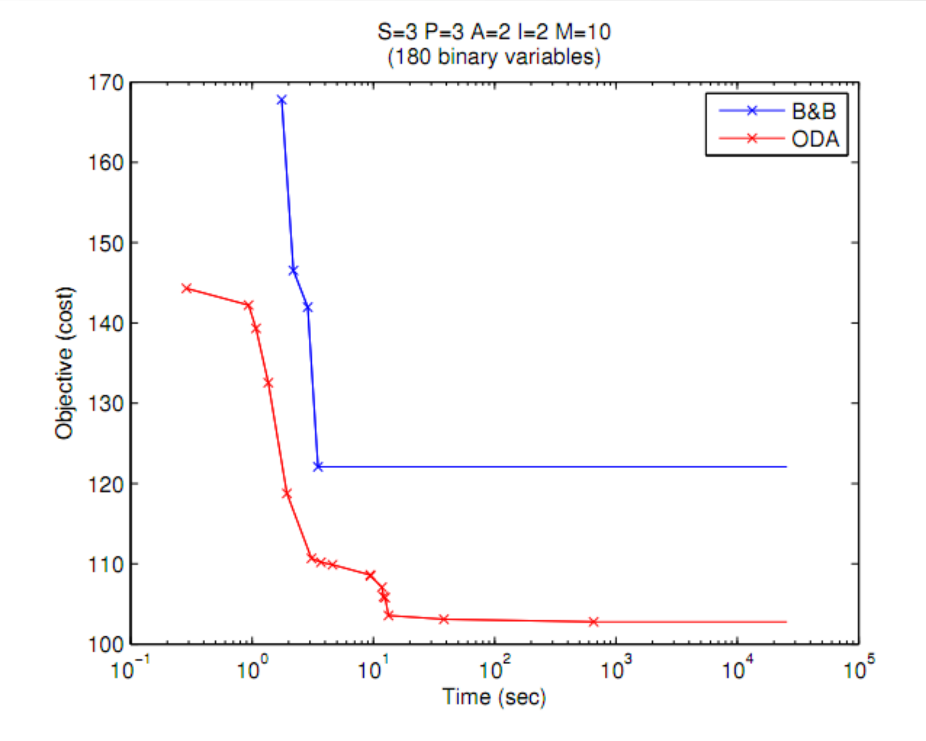
Preprocessed Cost Function





Experimental Results





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Broader overview of my DG research

- DG languages, semantics & reductions
  - For DB application developers (SQL, Xquery, JSONiq)
  - For software developers (CoJava)
  - For domain specific end-users
- DG algorithms
  - DG reduction algorithms
  - Process optimization by decomposition and pre-processing
  - Stochastic optimization of temporal processes through deterministic approximations
  - Regression of n-dimensional piece-wise linear functions
  - Classification over multivariate time series
  - Top-K recommendations using simulation and regression
  - Probabilistic algorithms to optimize recommendation diversity
- DG tools, systems & applications
  - Unity DGMS
  - Manufacturing, energy & power grids, supply chain, service networks, …
  - Package and group recommender systems, e.g., for investment in infrastructure, renewable energy, production capacity, …

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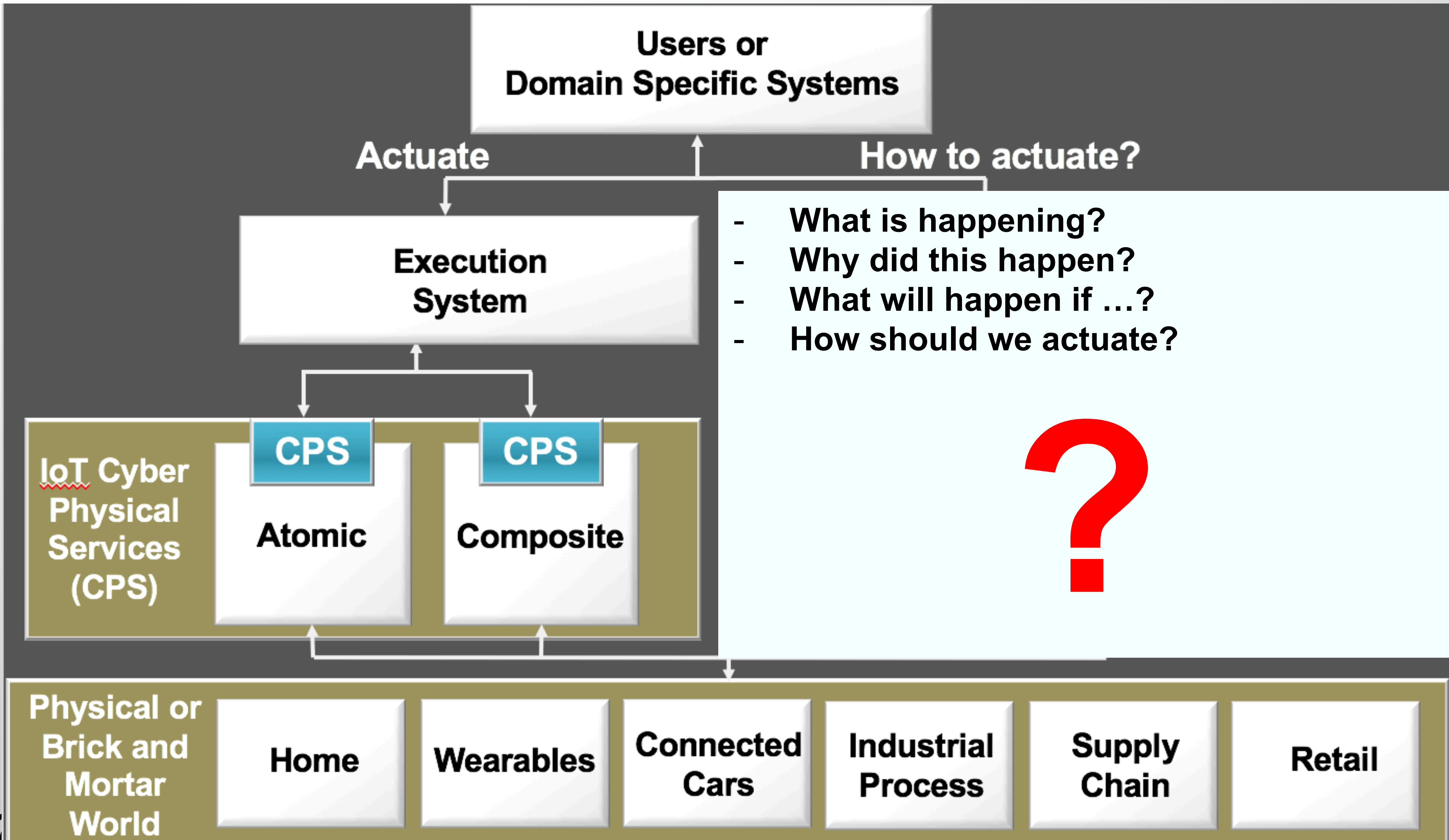
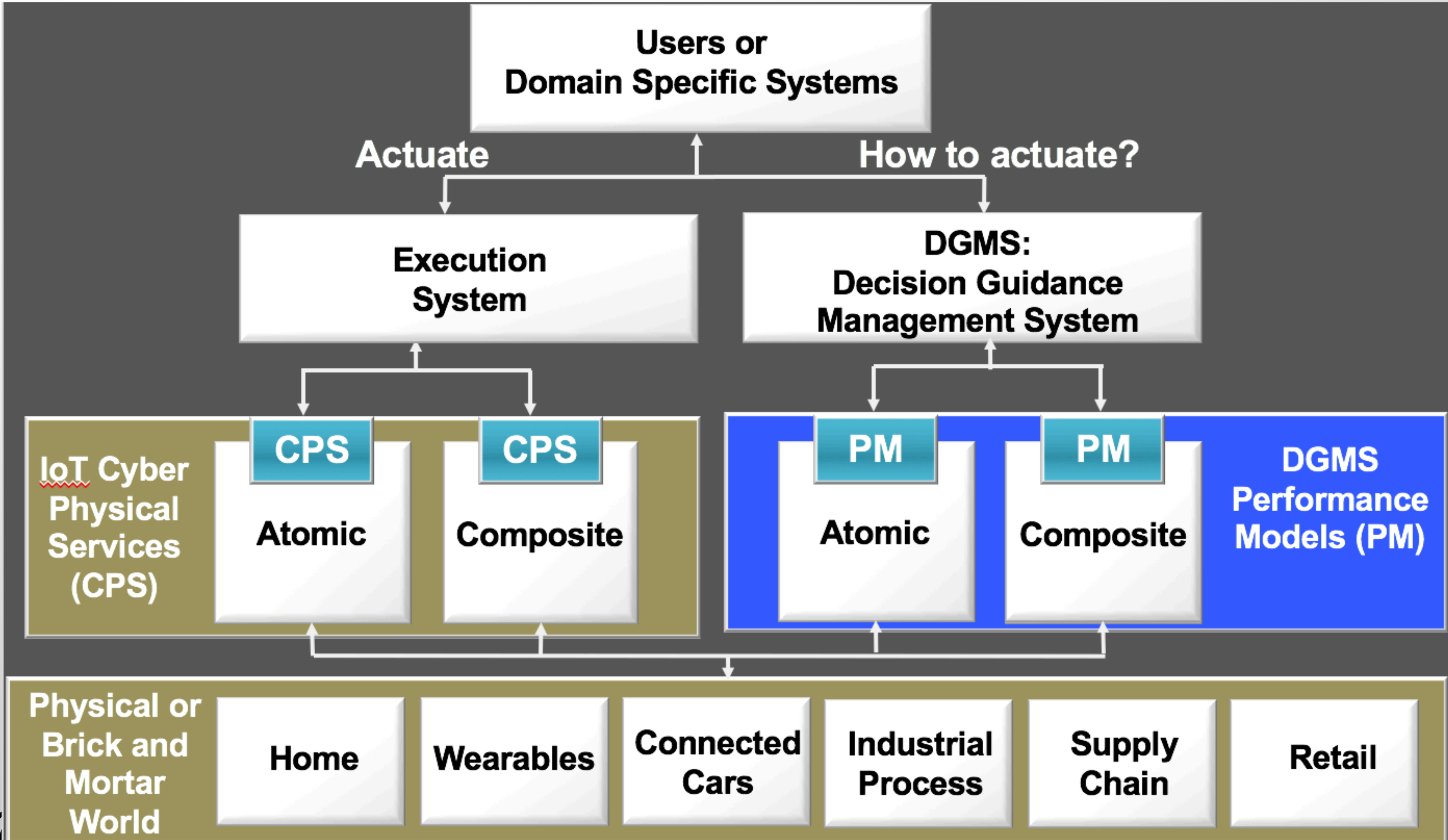
Question: IoT + ? = Cyber Physical Systems

features	Internet	SOA	IoT
Purpose & value	Easy Sharing of web content	Easy integration of heterogeneous IT systems	Easy development & operation of cyber physical systems (CPS)
Enable sharing of	Web-content	IT web services	IoT-enabled cyber physical services (CPS)
Enablers:	Internet protocols Stack: HTML, HTTP, TCP/IP	Web services protocols stack: • REST or SOAP -service API • Internet stack	IoT protocols stack
How to make sense of it?	Web search	Service discovery & composition: • WSDL – API description • UDDI - discovery • BPEL – composition & execution	?

Cyber physical systems = execution of IoT services + DG analytics



Cyber physical systems = execution of IoT services + DG analytics



Conclusions and future work

- Technical research challenges with impact on real-world problems
- Main goal: a robust DGMS
- DBMS have revolutionized the development of modern Information Systems
- Can DGMS have similar impact on the development of Decision Guidance Systems?
- Can DGMS significantly simplify the development of IoT cyber physical systems?

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Questions ???