The Application of Architecture Frameworks to Modelling Exploration Operations Costs

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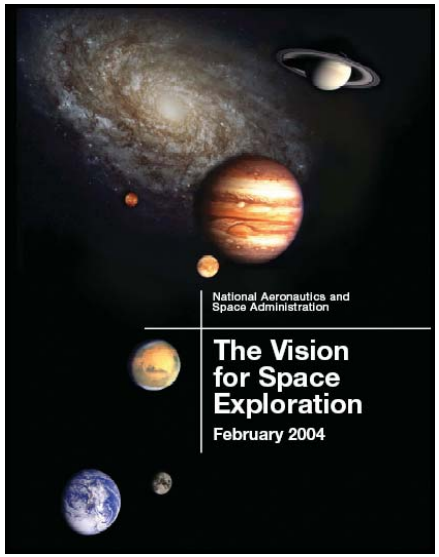
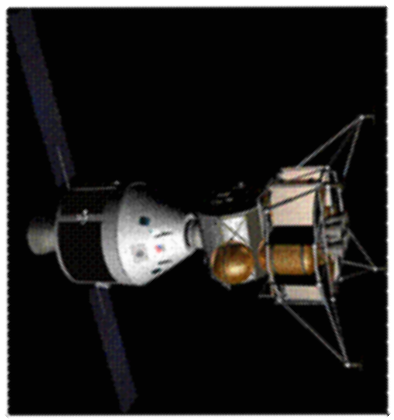
President's Vision for Space Exploration

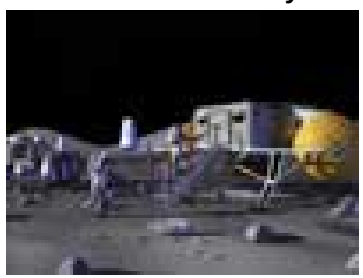


Constellation Program Elements

Flight Systems



Destination Surface Systems



Common Support Systems

Constellation Program is a Complex System-of-Systems

- Program-level SE requires trade studies to ensure that the selected architecture is “best” within available resources
- Need to integrate LCC considerations into these trade studies
  - Operations costs in human spaceflight programs are often the majority of LCC, and . . .
  - Early design decisions can often lock-in a high level of operations costs, yet . . .
  - Operations cost modeling hasn’t received the attention given to development cost modeling in NASA
- Modeling operations costs is different from development costs
  - Large number of different activities with different “cost drivers”
  - Operations costs should be modelled based on activity-appropriate engineering relationships/algorithms

Exploration Architectures Operations Cost Model (ExAOCM)

- It is possible to model operations costs for a complex SoS, like Constellation, by taking advantage of developments in architecture frameworks and system-of-systems thinking

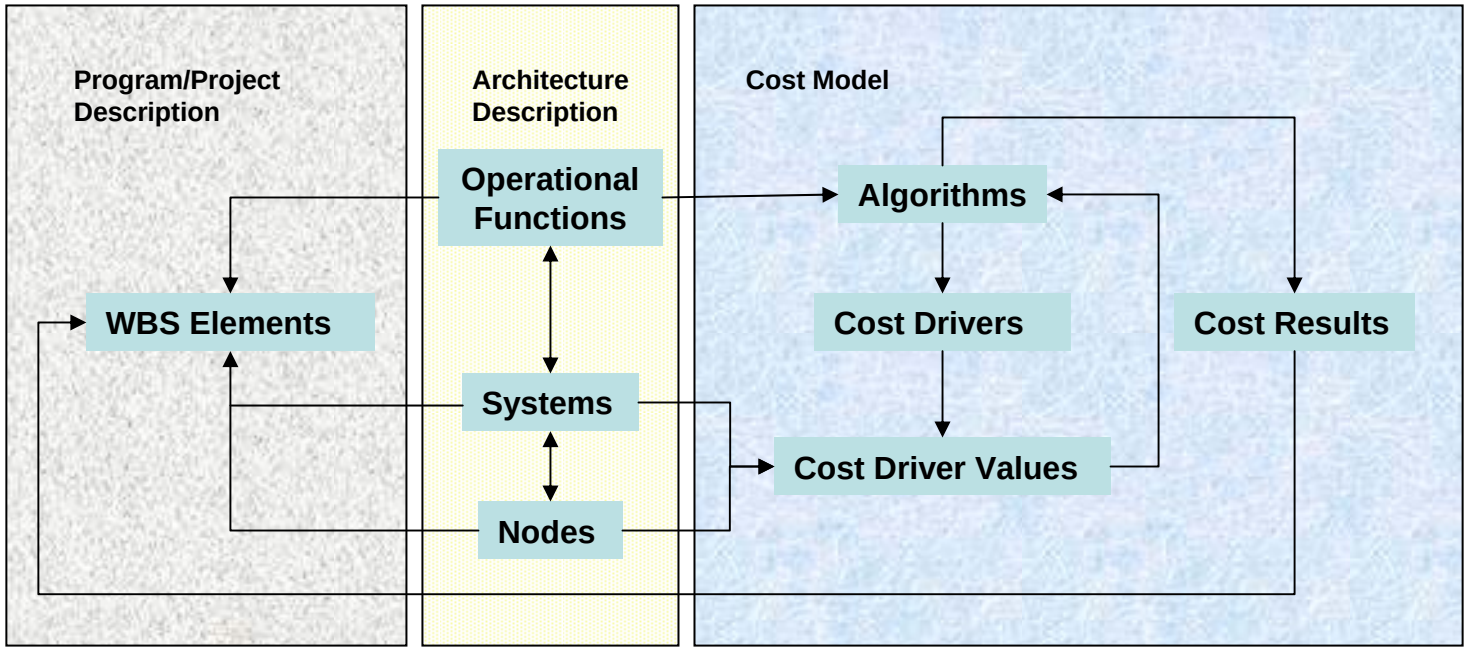
- DoDAF concepts, language, and formalisms provide a natural way of conceptualizing an exploration operations cost model (and other complex SoS) that will support integrated trade studies
  - Operational Nodes (OV-2)
  - Operational Functions/Activities (OV-5)
  - Systems (System Nodes (SV-1) and System Functions (SV-4))
  - Operational Functions/Activities to Systems/System Functions (SV-5)

- ExAOCM can be viewed as an evolution of operations cost modelling for SSF/ISS (MESSOC)

ExAOCM High-Level Functional Requirements

- The user shall be able to:
  - Assemble and visualize an exploration architecture consisting of multiple systems at multiple operational nodes, providing a specific set of capabilities.
  - From an operations concept, create multiple operations scenarios, apply operations rules, and crew policies
  - Introduce new operations technologies.
  - Develop a cost estimate based on causal/engineering relationships and/or analogy with ISS.
  - Apply probability distributions to develop a cost risk estimate.
  - The model shall be extensible in time (to 30 years) and space (to Mars human habitat).
- The model shall meet IM&S standards through NeXIOM conformance

Conceptual Flow From Exploration Architecture To Costed Operations WBS



Note: “Systems” box also encompasses “systems nodes” and “systems functions.”

Relationship to Other DoDAF "Products"

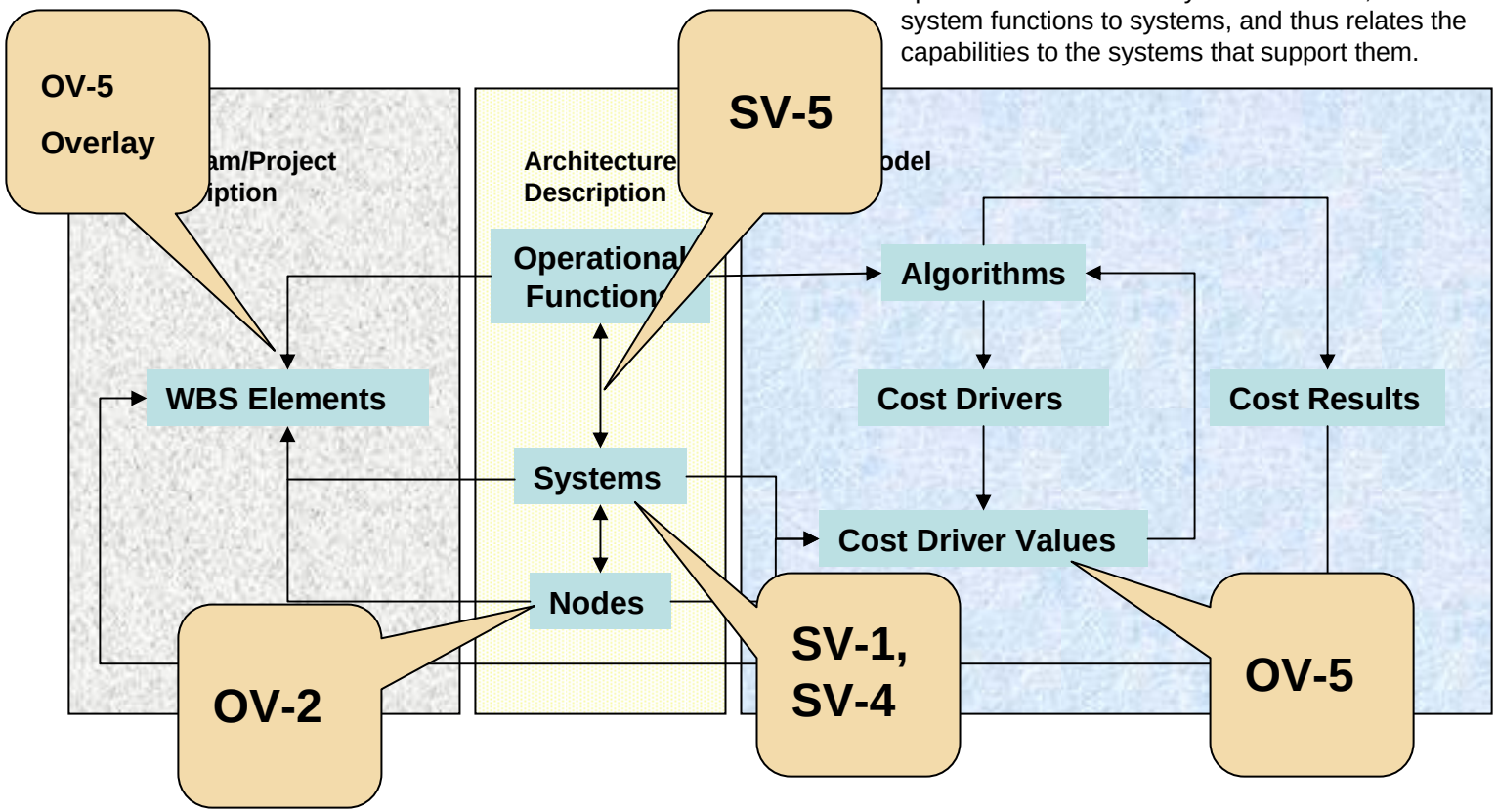
OV-2: Operational nodes, connectivity, and information exchange needlines between nodes

OV-5: Capabilities, operational activities, relationships among activities, inputs, and outputs; overlays can show cost, performing nodes, or other pertinent information

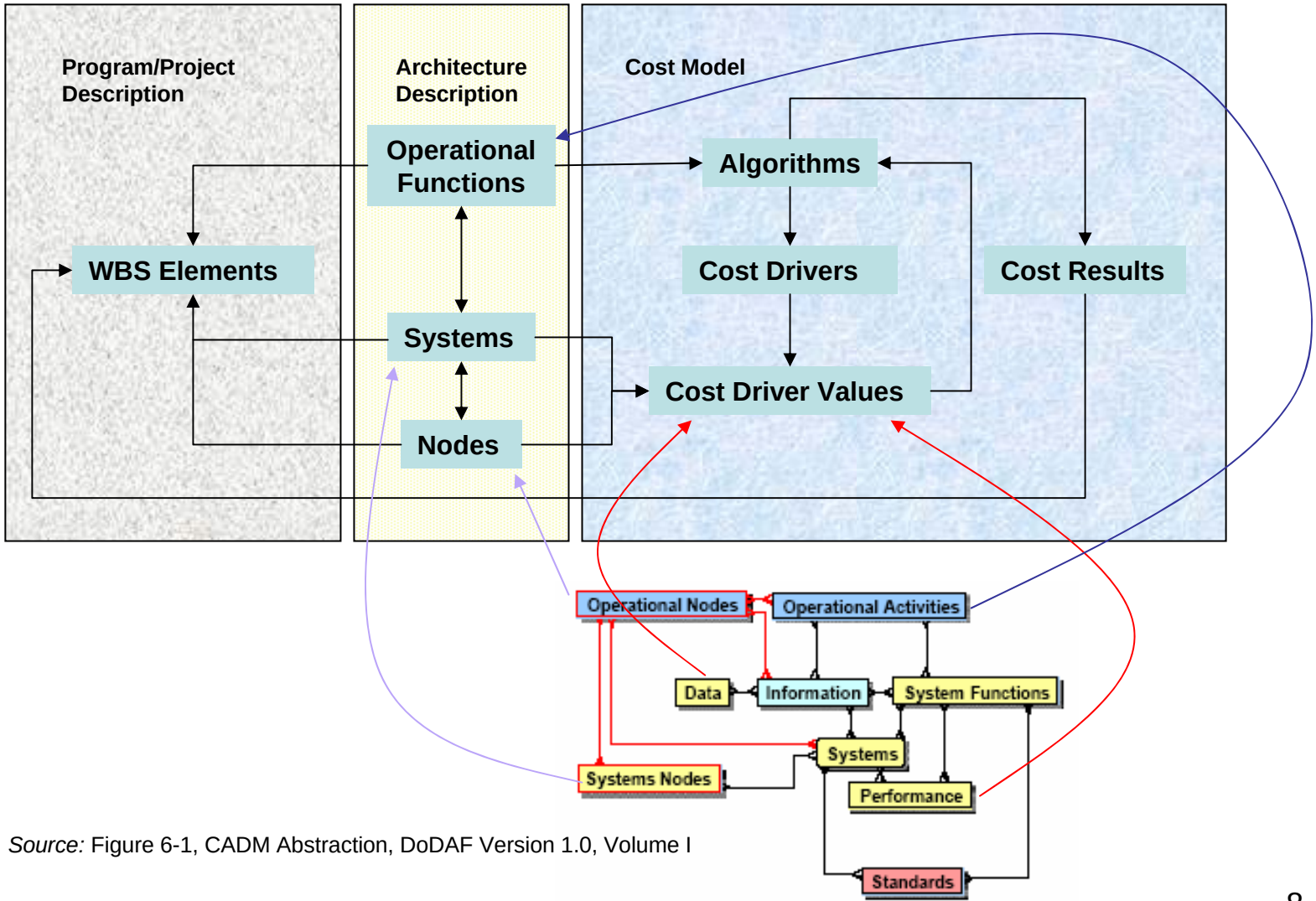
SV-1: Identification of systems nodes, systems, and system items and their interconnections, within and between nodes

SV-4: Functions performed by systems and the system data flows among system functions

SV-5: Maps capabilities to operational activities, operational activities to system functions, and system functions to systems, and thus relates the capabilities to the systems that support them.

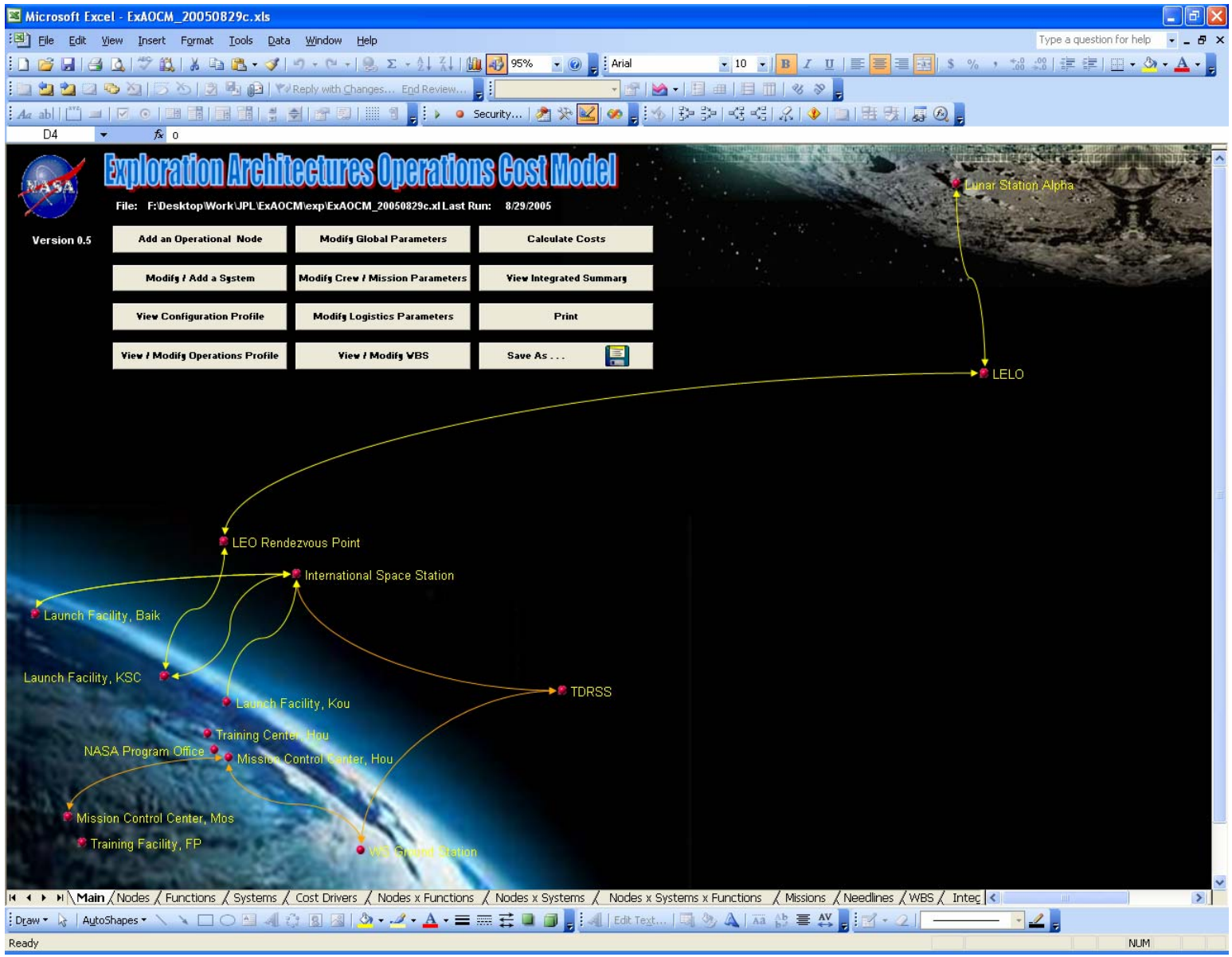


Relationship to Core Architecture Data Model (CADM)



Source: Figure 6-1, CADM Abstraction, DoDAF Version 1.0, Volume I

Main User Interface is a High-Level Graphic (OV-1)



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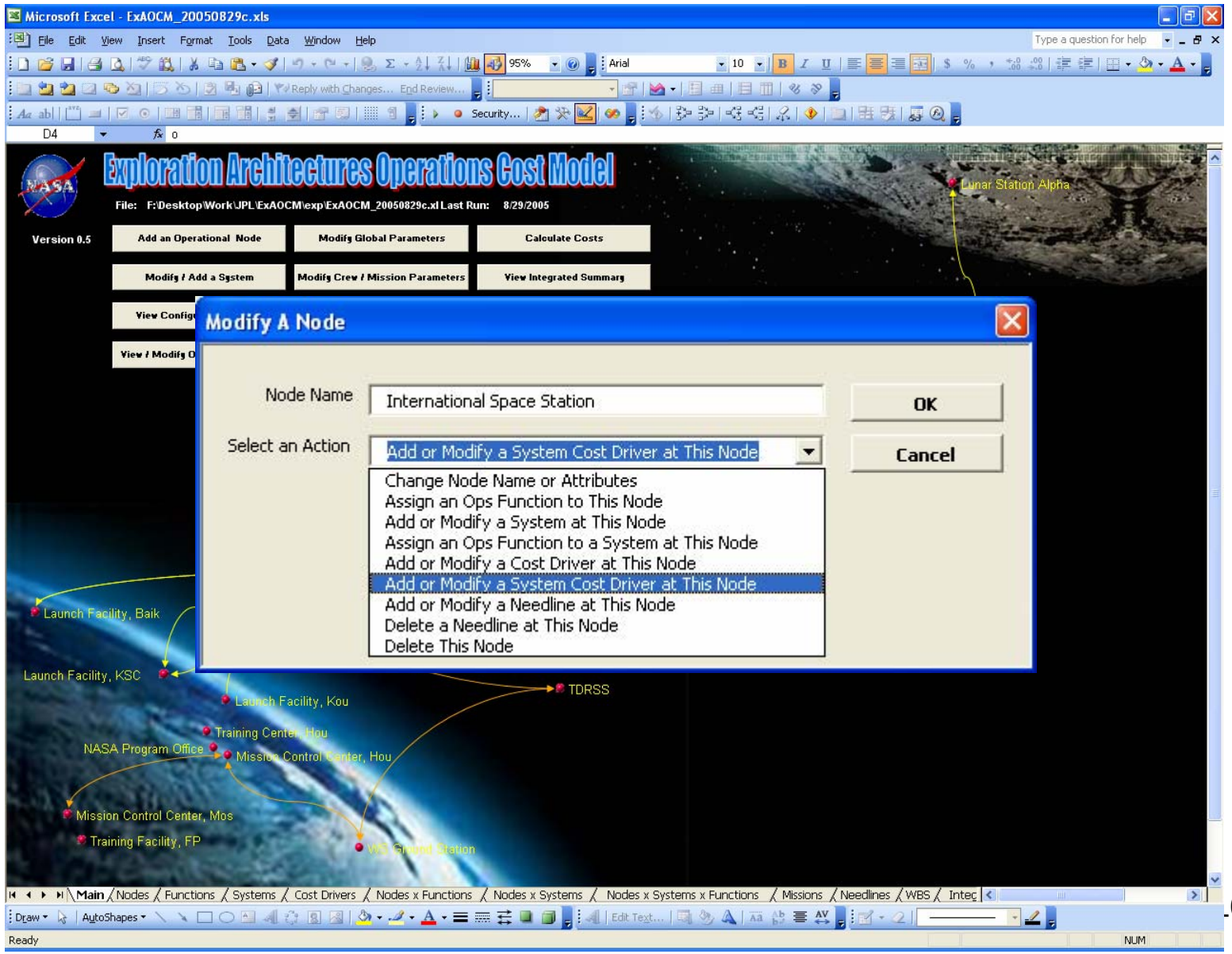

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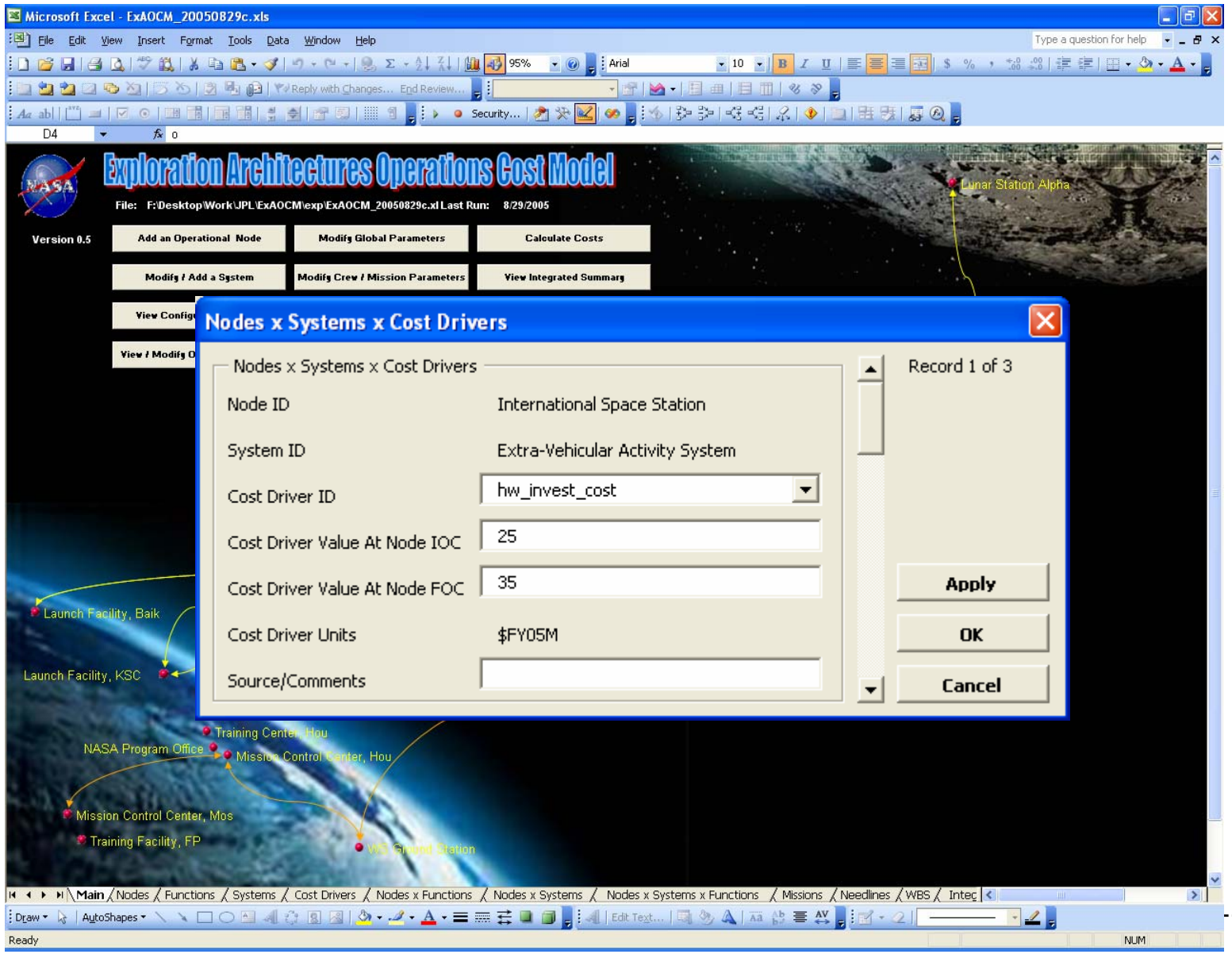
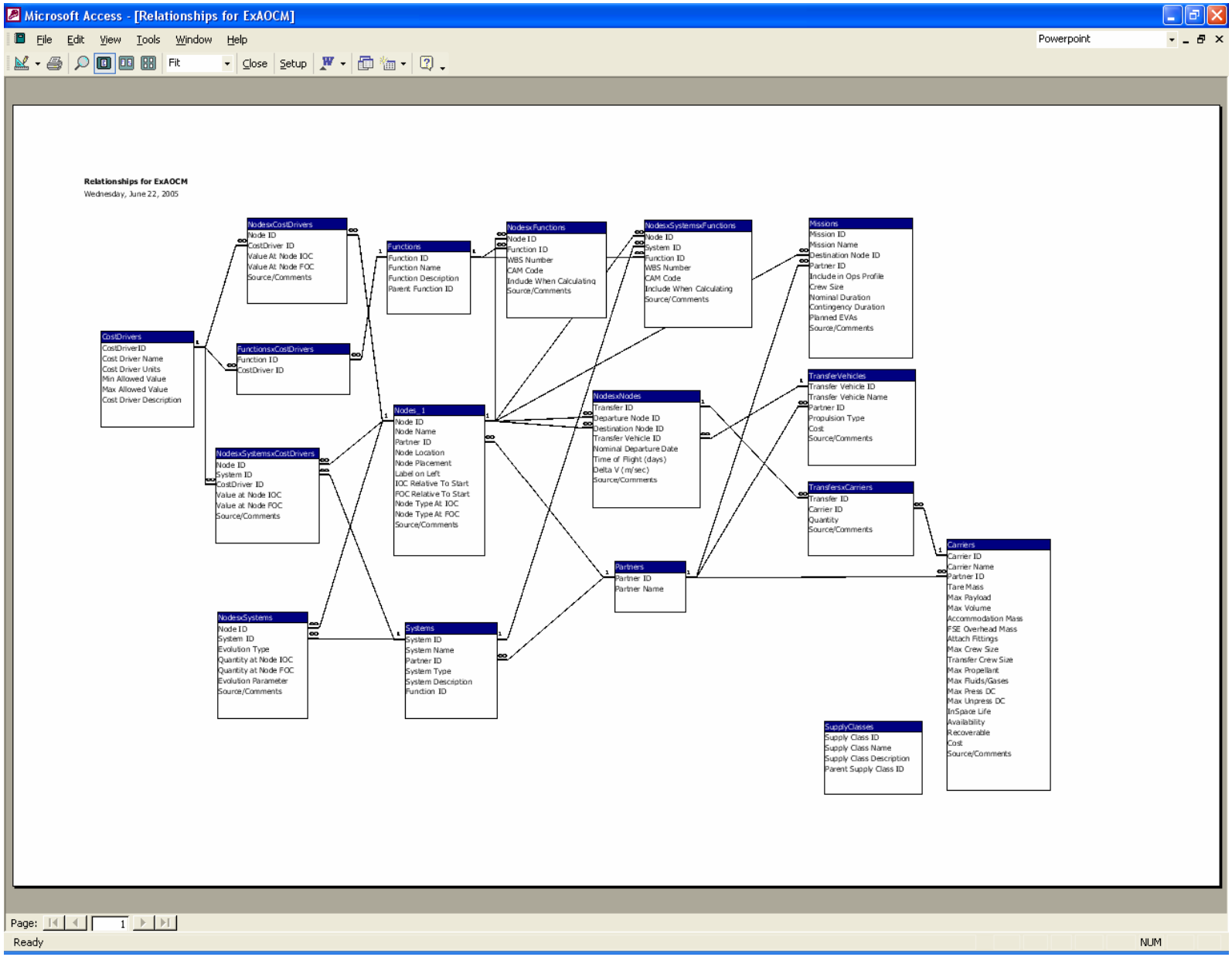


Datatables in ExAOCM



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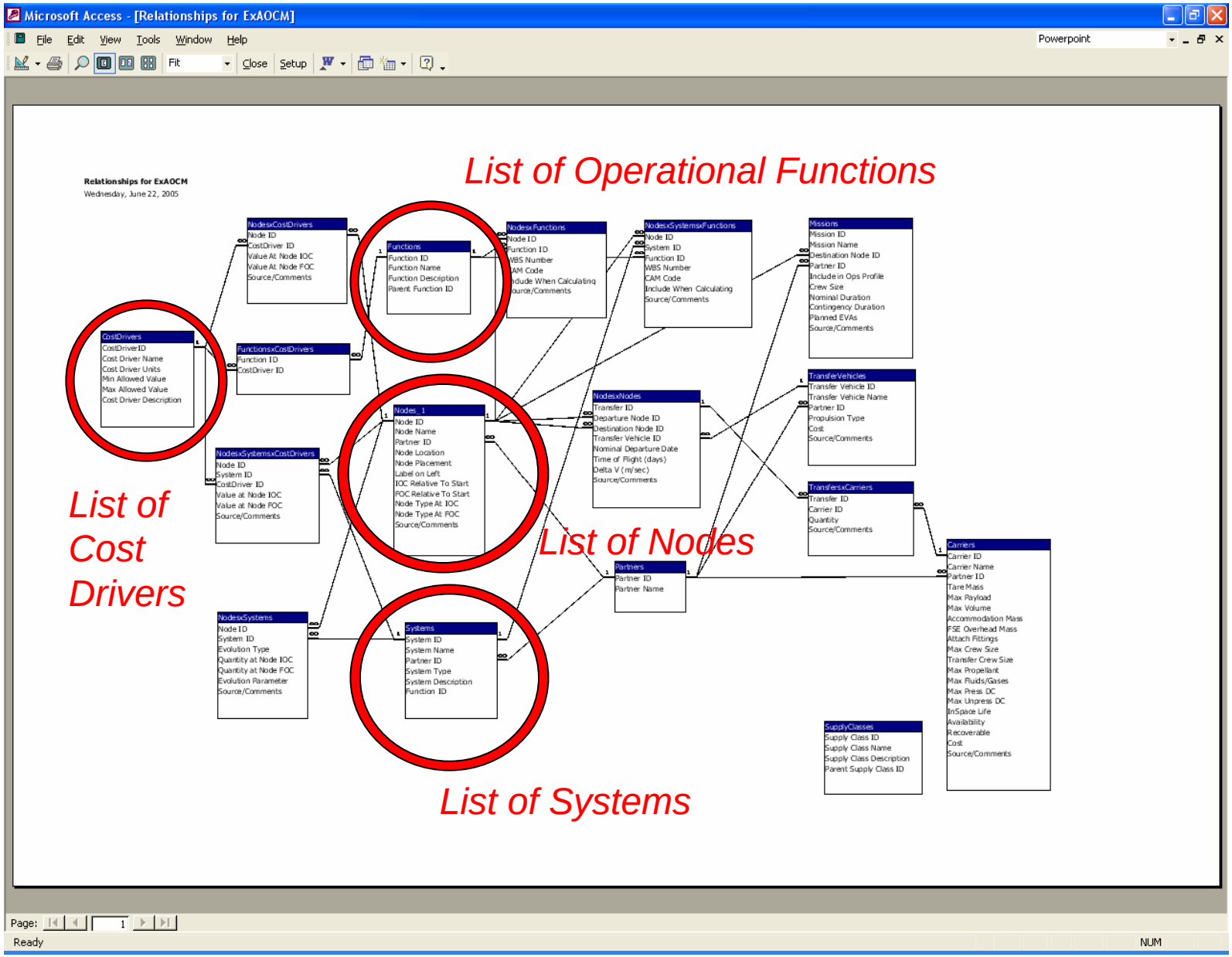

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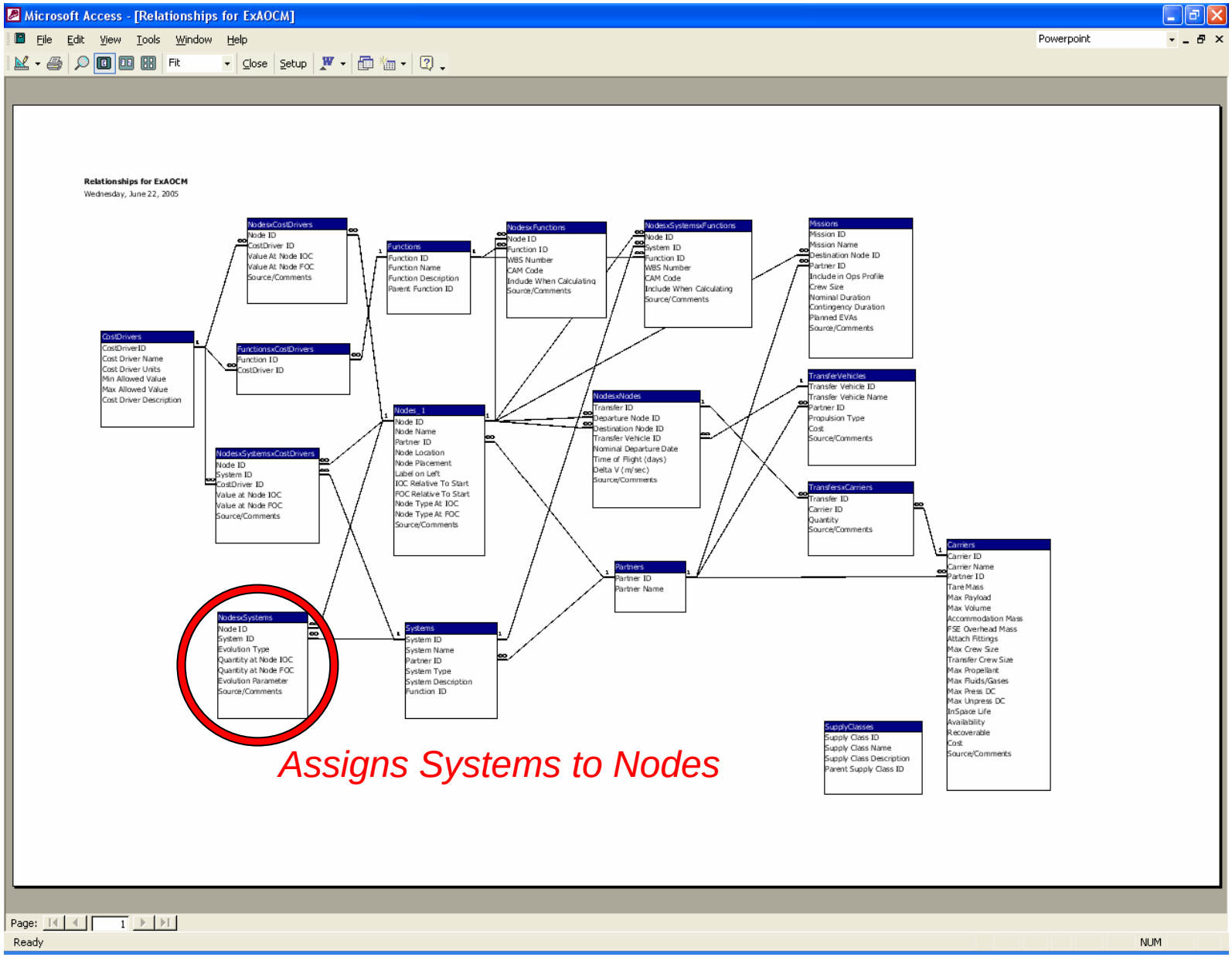

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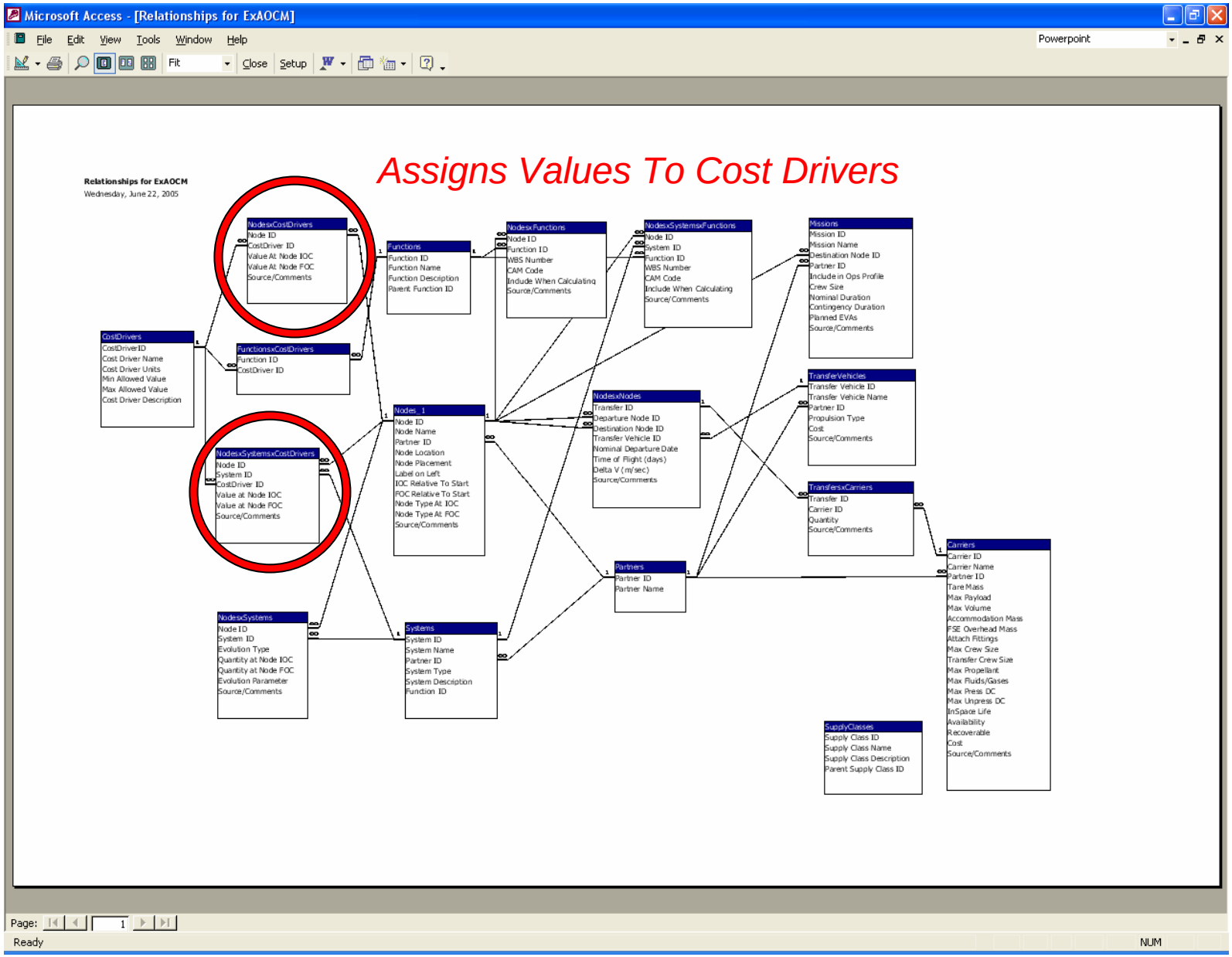

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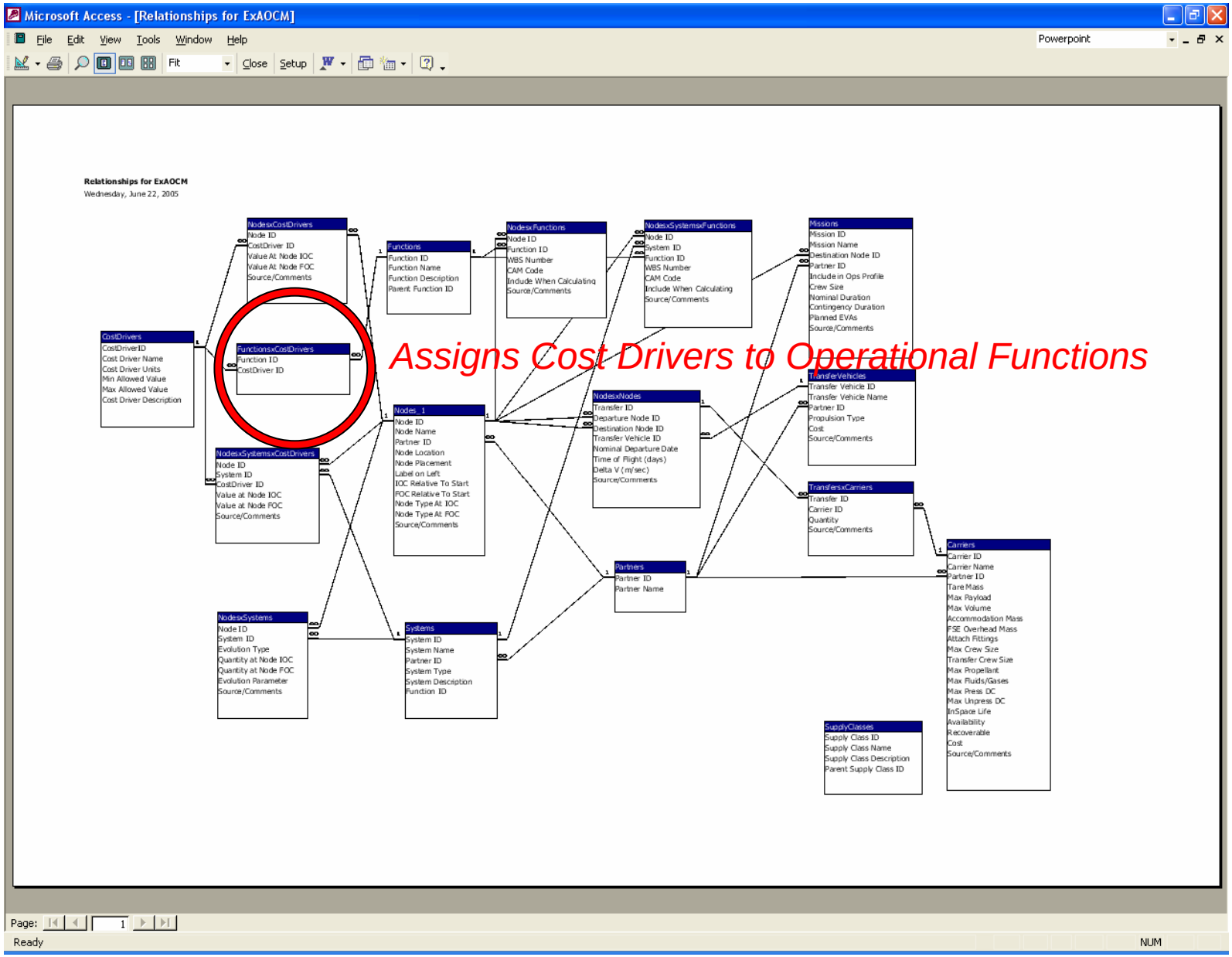
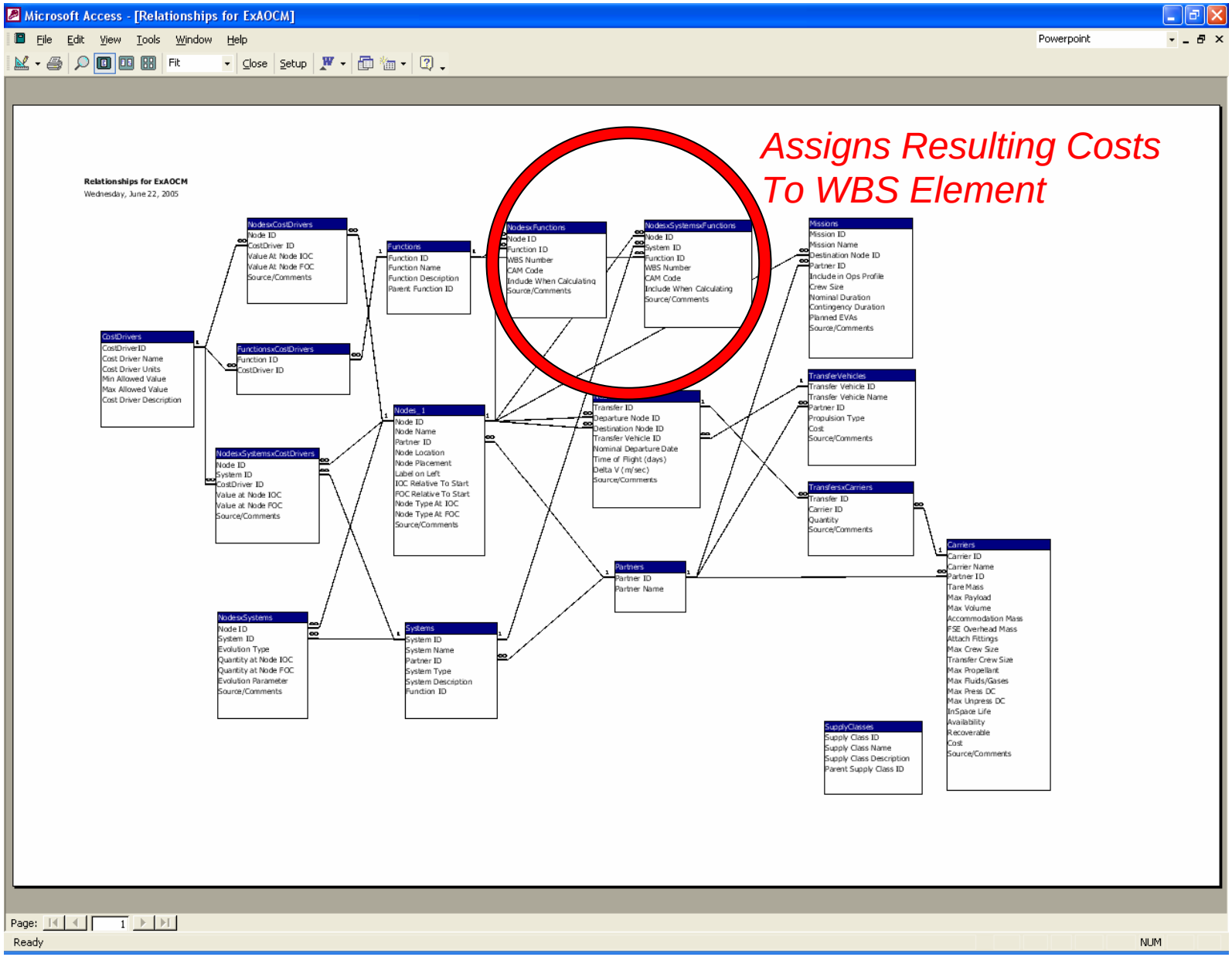


Datatables in ExAOCM



Datatables in ExAOCM Systems

Systems

Describes System By Content, Type, System Function

System ID	System Name	System Short Name	Partner ID	System Description	System Type	System Function
1	Extra-Vehicular Activity System	EVA	1	EMU, LSS, SAFER, EVA tools, translation aids	1	Supports external maintenance and scienc
2	Integrated Planning System	IPS	1	HW/SW for mission timelining and execution	4	Supports flight planning and execution
3	Mission Control Center Facility	MCC-A	1	Flight control front and backrooms	4	Supports flight preparation and execution
4	Flight Controller Training Facility	FCT	1	Flight controller consoles and communications for training	4	Supports flight controller training
5	Shuttle Mission Training Facility	SMTF	1	SST, NSS, GNS, Fixed Base and Motion Base sims	6	Supports flight crew training
6	FDD Infrastructure System		1	Flight design and dynamics H/W and S/W development environmer	4	Supports flight design

System Ownership

Datatables in ExAOCM
Nodes x Systems

Systems Assigned To Each Node

Describes How/When System Quantity Evolves At Each Node

Node ID	System ID	System Name	System Qty Evolution Type	Quantity At Node IOC	Quantity At Node FOC	Evolution Parameter	Source/Comments
1	2	Integrated Planning System	0	1	1		
1	3	Mission Control Center Facility		1	1		
1	6	FDD Infrastructure System		1	1		
8	4	Flight Controller Training Facility		1	1		
8	5	Shuttle Mission Training Facility		1	1		
7	1	Extra-Vehicular Activity System	1	4	7	12	
2	1	Extra-Vehicular Activity System	1	4	8	3	

Lunar Base Alpha

Training Center, Houston

Quantity Evolution

Mission Control Center, Houston

Datatables in ExAOCM
Cost Drivers

Cost Driver

Describes Cost Driver

Cost Driver ID	Cost Driver Name	Cost Driver Units Type	Min Allowed Value	Max Allowed Value	Cost Driver Description
1	hw_invest_cost	4	0		Investment cost for hardware assets
2	mass_effective	8	0		Mass of element/system
3	sw_kslocs	2	0		Software source lines of code in thousands excluding comments
4	mgmt_support_factor	2	0	1	Management and adminstration overhead factor
5	prog_volatility	2	0	2	Program/project volatility considering schedule, payload, or mission changes,
6	mission_complexity	2	0.7	1.7	Mission complexity relative to STS mission
7	cev_vehicle_complexity	2	0.7	1.7	CEV complexity relative to STS
8	grd_system_complexity	2	0.7	1.7	Ground system complexity relative to STS ground system
9	num_monitored_cev_systems	1	0		Number of console positions driven by CEV system
10	telemetry_automation_factor	2	0.7	1.7	Degree of telemetry automation relative to STS
11	command_automation_factor	2	0.7	1.7	Degree of command automation relative to STS

Cost Driver Units

Minimum and Maximum Allowed Values

Datatables in ExAOCM
Nodes x Systems x Cost Drivers

System Assigned To This Node

Describes How System Cost Driver Evolves At This Node

Node ID	System ID	Cost Driver ID	System Name	Cost Driver Name	Cost Driver Value At Node IOC	Cost Driver Value At Node FOC	Cost Driver Units	Source/Comments
1	6	3	FDD Infrastructure System	sw_kslocs	5203	5203	real, dimensionless	
1	6	6	FDD Infrastructure System	mission_complexity	1	1	real, dimensionless	
1	2	5	Integrated Planning System	prog_volatility	1	1	real, dimensionless	
1	3	8	Mission Control Center Facility	grd_system_complexity	1	1	real, dimensionless	
1	3	10	Mission Control Center Facility	telemetry_automation_factor	1	1	real, dimensionless	
1	3	11	Mission Control Center Facility	command_automation_factor	1	1	real, dimensionless	
7	1	1	Extra-Vehicular Activity System	hw_invest_cost	25	35	$FY05M	
7	1	2	Extra-Vehicular Activity System	mass_effective	225	450	kg	
8	5	3	Shuttle Mission Training Facility	sw_kslocs	8510	8510	real, dimensionless	

Training Center, Houston

Cost Driver

Mission Control Center, Houston

Datatables in ExAOCM
Nodes x Systems x Function

Systems Assigned To Each Node

Assigned WBS and CAM Code

Node ID	System ID	System Name	Function ID	Function Name	WBS	CAM Code	Include When Calculating (T/F)	Source/Comments
1	2	Integrated Planning System	2	Facility/System Management	4.3.2.1.1	DA	TRUE	
1	2	Integrated Planning System	3	Facility/System Operations	4.3.2.1.3	DA	TRUE	
1	2	Integrated Planning System	4	Facility/System Hardware Maintenance	4.3.2.1.4.1	DA	TRUE	
1	2	Integrated Planning System	5	Facility/System Software Maintenance	4.3.2.1.4.2	DA	TRUE	
1	2	Integrated Planning System	6	Facility/System Sustaining Engineering	4.3.2.1.5	DA	TRUE	
1	3	Mission Control Center Facility	2	Facility/System Management	4.3.2.2.1	DA	TRUE	
1	3	Mission Control Center Facility	3	Facility/System Operations	4.3.2.2.3	DA	TRUE	
1	3	Mission Control Center Facility	4	Facility/System Hardware Maintenance	4.3.2.2.4.1	DA	TRUE	
1	3	Mission Control Center Facility	5	Facility/System Software Maintenance	4.3.2.2.4.2	DA	TRUE	
1	3	Mission Control Center Facility	6	Facility/System Sustaining Engineering	4.3.2.2.5	DA	TRUE	
8	4	Flight Controller Training Facility	2	Facility/System Management	4.3.3.2.1.1	DA	TRUE	
8	4	Flight Controller Training Facility	3	Facility/System Operations	4.3.3.2.1.3	DA	TRUE	
8	4	Flight Controller Training Facility	4	Facility/System Hardware Maintenance	4.3.3.2.1.4.1	DA	TRUE	
8	4	Flight Controller Training Facility	5	Facility/System Software Maintenance	4.3.3.2.1.4.2	DA	TRUE	
8	4	Flight Controller Training Facility	6	Facility/System Sustaining Engineering	4.3.3.2.1.5	DA	TRUE	
8	5	Shuttle Mission Training Facility	2	Facility/System Management	4.3.3.2.2.1	DA	TRUE	
8	5	Shuttle Mission Training Facility	3	Facility/System Operations	4.3.3.2.2.3	DA	TRUE	
8	5	Shuttle Mission Training Facility	4	Facility/System Hardware Maintenance	4.3.3.2.2.4.1	DA	TRUE	
8	5	Shuttle Mission Training Facility	5	Facility/System Software Maintenance	4.3.3.2.2.4.2	DA	TRUE	
8	5	Shuttle Mission Training Facility	6	Facility/System Sustaining Engineering	4.3.3.2.2.5	DA	TRUE	
1	6	FDD Infrastructure System	2	Facility/System Management	4.3.4.3.3.1	DA	TRUE	
1	6	FDD Infrastructure System	3	Facility/System Operations	4.3.4.3.3.3	DA	TRUE	
1	6	FDD Infrastructure System	4	Facility/System Hardware Maintenance	4.3.4.3.3.4.1	DA	TRUE	
1	6	FDD Infrastructure System	5	Facility/System Software Maintenance	4.3.4.3.3.4.2	DA	TRUE	
1	6	FDD Infrastructure System	6	Facility/System Sustaining Engineering	4.3.4.3.3.5	DA	TRUE	

Mission Control Center, Houston

Training Center, Houston

Describes the Operational Function

MOD Model Equations Are Linear in Flight Rate

$$Wkhrs_i(T) = a_i(x_1, x_2, \ldots, x_n) + \sum_{t=T,T+1,T+2} b_i(x_1, x_2, \ldots, x_n; t) Q_t$$

Workhours for function i

"Generic" workhours for function i

Variable workhours for function i

Flight rate

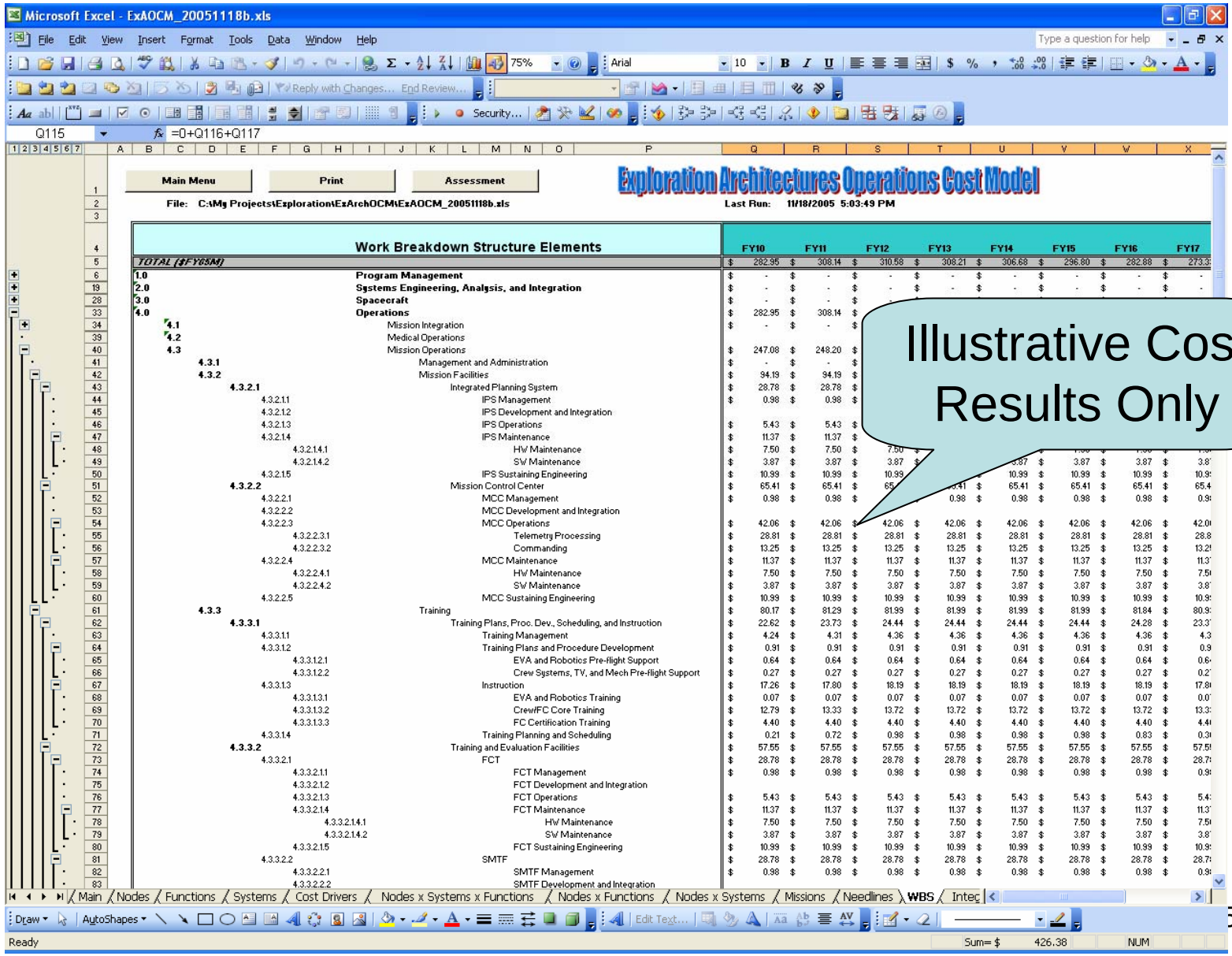
e.g., mission design complexity, crew size, program volatility, ground system complexity, function KSLOCs, etc.

$$TotalWkhrs(T) = \sum_i Wkhrs_i(T)$$

ExAOCM Pseudocode

```
Do some housekeeping
Step through Operational Functions
Determine Cost Drivers for this Operational Function
        Step through Nodes/Systems
                Determine whether this Node performs this Operational Function
                If so, determine appropriate WBS Element
                Step through Time
                        Determine value of each Cost Driver at this Time
                        Estimate Cost
                        Write to correct WBS Element and Time
                Next Time
        Next Node/System
Next Operational Function
Do some housekeeping
```

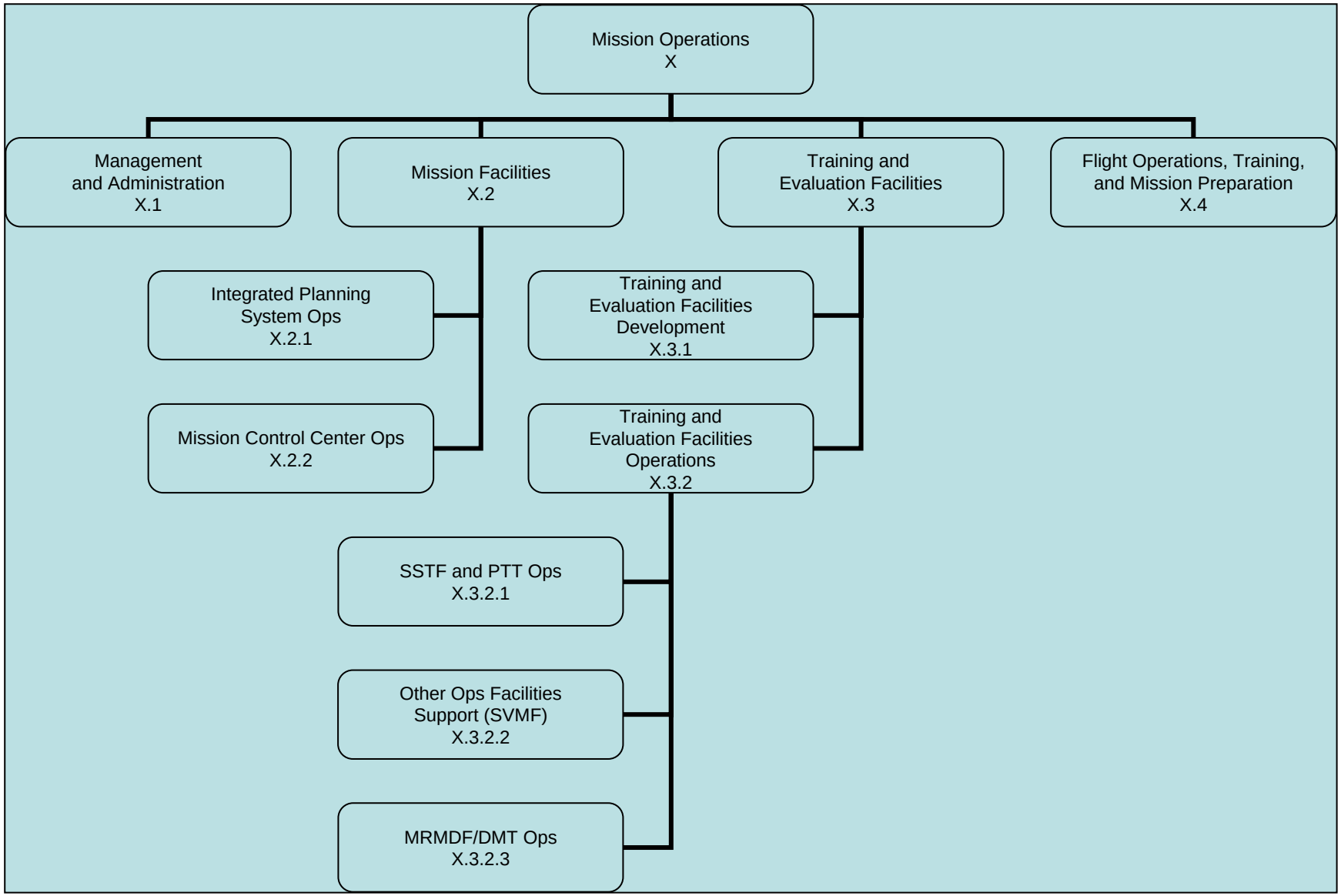
Cost Model Results



Illustrative Cost Results Only

Observations and Conclusions

- DoDAF concepts, language, and formalisms provide a natural way of conceptualizing an exploration operations cost model.
- Suggests some products/tables that might be added to DoDAF/CADM to strengthen the architecture framework's relationship to cost.
- Need a WBS for operations tied to specific functions occurring at operational nodes, and/or to specific functions performed on systems at operational nodes.
- Approach is sufficiently generic to be a useful way of modelling operations costs in other programs (e.g., robotic space missions, NOAA/JOI, net-centric defense architectures)

Backup

ISS Work Breakdown Structure Rev. B (March 2004)