Developing and Modeling an Approach for Requirements Management Optimization

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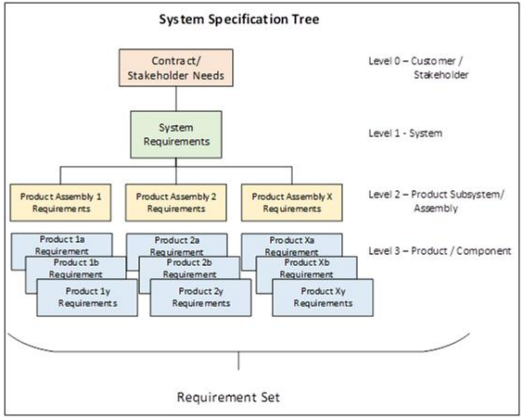
Overview

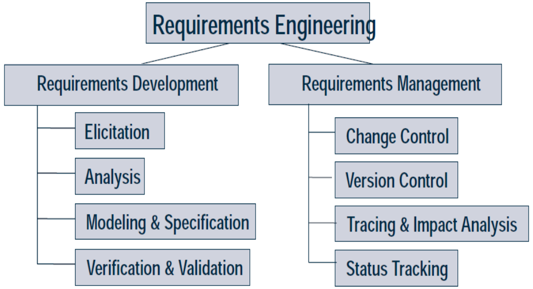
- Introduction of Requirements Management Challenges
- Proposed Optimization of Requirements Management Process Models
- Process Model Simulations and Results
- Final Recommendations

Requirements Engineering Concepts

- A **Requirement** is a statement which translates or expresses a need and its associated constraints and conditions in a very specific, precise and unambiguous manner.
- Requirements at the system are allocated to the system elements and decomposed to the lower levels of abstraction; these are aligned with the system requirements through traceability and reflected in a systems specification tree.

- **Requirements Management** consists of activities that identify, document, maintain, communicate, trace and track requirements throughout the life cycle of a system, product or service.
- Per Hood, et al., "while requirements development assures that what is to be developed is indeed what the customer wants, requirements management integrates the data created during requirements development into the overall project flow." (Hood, Wiedemann, Fichtinger, & Pautz, 2008).





Requirements Engineering Processes (Pohl, 2010)

Why Optimize the Requirements Management Process?

- Based on research and experience, the following observations have been noted:
  - A complex system can have thousands of requirements across multiple levels for several dozen products.
  - Transforming customer *needs* to product *requirements* is an iterative process, requiring some knowledge of the design, and takes schedule.
  - Suppliers often need to be put on contract early to begin their development efforts, bringing a need for their requirements early in the program lifecycle.
  - Resources required to address thousands of requirements can be large, and not always within the allowable budget of the system provider.
  - For many of today's space systems the need to be affordable and fast are a reality with changing technology and competitive markets.

- **Research into managing complex space systems showed that Requirements Management can enable, or negatively impact, project success.**

SPACENEWS

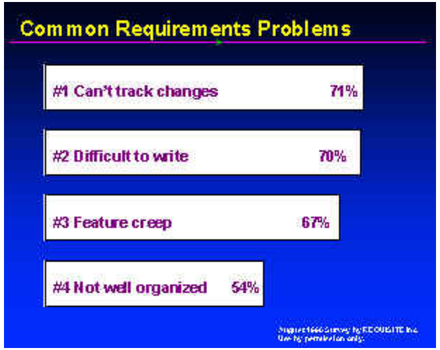
SpaceX Says Requirements, Not Markup, Make Government Missions More Costly

by Peter B. de Selding — March 27, 2014

SPACENEWS

Changing NASA requirements caused cost and schedule problems for Gateway

by Jeff Foust — November 12, 2020



Common Requirement Issues (Rational Software Corporation, 1999)

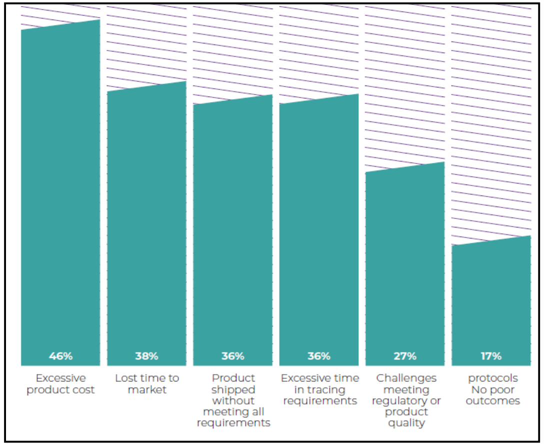
Cost of Poor Requirements Engineering

- One NASA study showed that projects which spend less than 5% of total project costs on the requirements engineering process experienced an **80% to 200% cost overrun**, whereas those that invested 8% to 14% were able to meet their costs or incur less than 60% overrun (Gruhl, 1992).
- Another study by NASA showed that **it can cost over 50 times** to correct a system due to a requirement error when the error is found during the test phase than if discovered during the requirements development activity (Stecklein, 2004).
- A 2018 Engineering.com survey report noted that only 15% of respondants worked in organizations that invested in a formal, dedicated requirements management solution, which resulted a variety of **impacts to project success** (Engineering.com, 2018).
- A study related to software safety found that most **accidents** related to software in the aviation industry stem from requirements problems, particularly related to incompleteness of the requirements (Howard & Anderson, 2002).

Cost to Fix Requirements Error (in Ratios)
Composite of Studies

Requirements	Design	Code	Test	Post-Deployment
1 (baseline)	5x	10x	50.5x	n/a

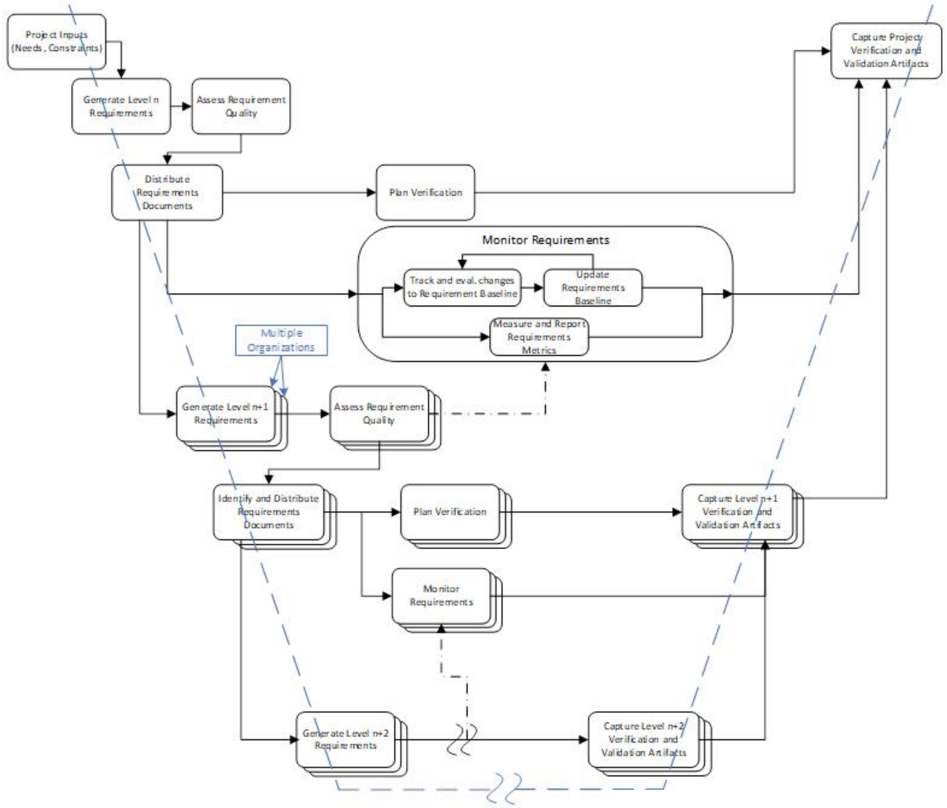
NASA paper, "Error Cost Escalation Through the Project Life Cycle" (2004)



Types of Failures due to Poor Requirements Management. (Engineering.com, 2018)

Capturing A Current Requirements Management Process Model

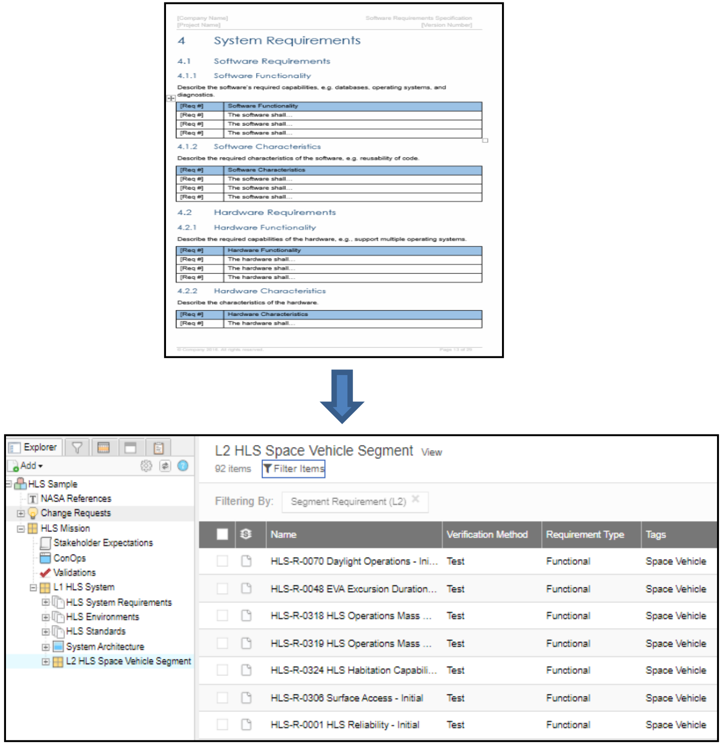
- Performing a literature research yielded development of a process model for requirements management on a system.
- This model provides a high level look at the processes, where details of each process step could be further refined in separate diagrams.
- The focus of this model is on management of the requirements as they are developed, distributed to the developers, monitored and updated as they mature.
- The requirements development effort itself can frequently iterate as the design matures, there are several models that refine that process further and it is not a focus of this particular study.



REQUIREMENTS MANAGEMENT PROCESS MODELS – PROPOSED OPTIMIZATION

Research into Requirements Management Challenges

- Through research into current approaches, newer trends and challenges noted by practitioners, the following observations on requirements management are noted:
  - Project cost is a function of **requirement quantity** and **quality**.
  - There is a movement **away from a document centric** approach and **towards a data centric approach of managing** the project's requirements, minimizing the usage of documents or compartmentalization of the requirements and combining requirements to an overall project repository.
  - **Use of requirements management tools** can enable requirements development, collaboration, change control, and trace to other project data.
  - Careful planning on **when to start change control** on requirements is needed, too soon or too late can have impact to project execution, and controlling too many requirement attributes can drive schedule.

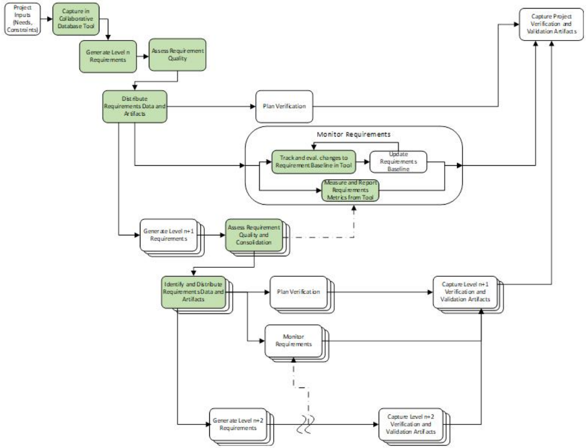


Movement Towards More Data Centric Requirements Management Method and Tools, such as Jama Connect

Proposed Process Areas to Optimize

- Based on the research, four requirements management process areas were identified for further optimization.
- These areas fall within the overall model in the green highlighted processes shown.

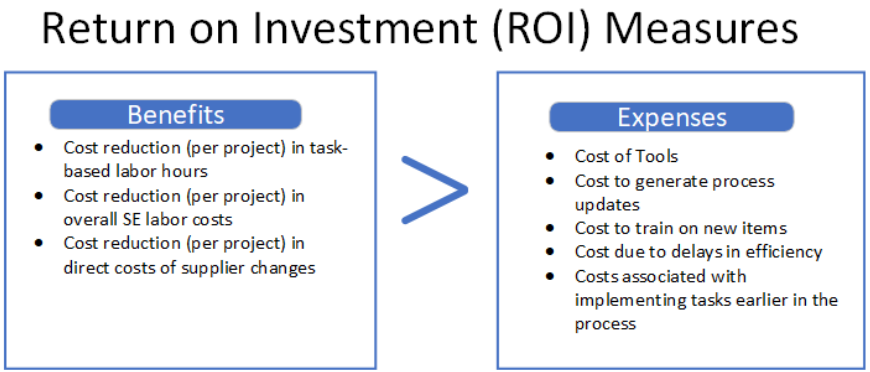
Identifier	Proposed Process Update
1	Implement a data focused requirements management approach
2	Utilize a management tool that supports electronic collaboration during requirement development and change activities throughout the project life cycle
3	Minimize and consolidate the requirements for the system of interest
4	Coordinate the timing between developing requirements and levying them officially



Hypothesis: Each of the four recommended approaches will provide cost optimization over current approaches, enabling selection of process improvement options for programs to apply.

Evaluation Measures for Requirements Management Processes

- When considering the application of process activities, a few parameters can be used to assess whether the new approaches add value for the project. These considerations include:
  - Cost of application and maintenance of the new process (Expenses)
  - Cost savings associated with labor and direct cost of the project-specific requirements management processes (Benefits)



The next set of slides provide the approach to measured cost savings between current state and proposed optimized methods for the four process areas presented.

Calculating Return on Investment (ROI)

- **Task labor hours:** Process execution labor costs can be calculated from labor hours associated with various tasks in the requirements management processes, providing measures for cost comparison.
  - For this project only specific tasks were assessed to allow a comparison, this is not an absolute measure of total time of the overall process.

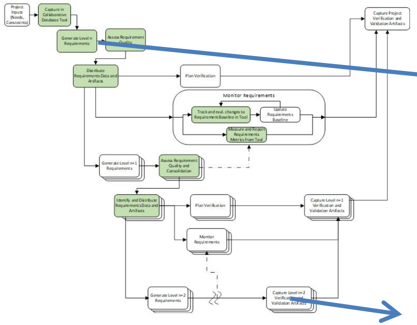
- **Project SE labor hours:** The cost model tool COSYSMO, which predicts systems engineering labor in labor months as a function of requirement quantity and quality, provides a measure of overall project systems engineering labor cost.

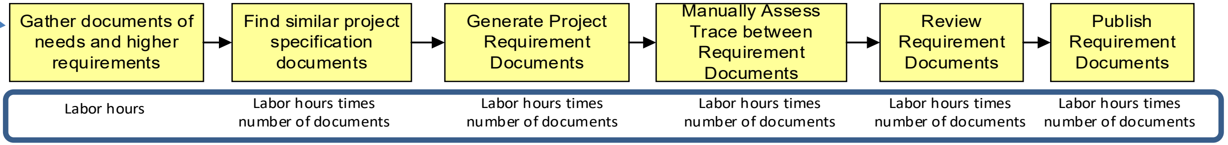
- **Direct Costs of Supplier Changes:** Direct costs associated with supplier changes can be obtained based on project parameters for supplier cost profiles (heritage), schedule of product need and associated delay costs, and requirement maturity.

Process Task Durations

- Estimated labor hours were provided for the tasks in each process being evaluated using a **range** of durations to allow for variation in skill and experience.
- The values were obtained from this author's experiences and observations to show how processes compare to one another; **these are not absolute measures** for a project to calculate a total time effort related to the project's process implementation.
- **Comparable tasks** for each set of processes were given **similar ranges of durations** (normalized to enable basis of comparison and due to lack of actual project data available for this analysis).

Task Name	Duration	Rationale
Gather documents of needs and higher requirements	40h..160h	Observation associated with collecting needs for an effort, going through assessment of use cases, contracts, higher documents, applicable standards; effort can take 1-4 weeks to obtain the inputs for requirement development.
Find similar project specification documents	20h..30h	Observation associated with generation of requirements on past projects with respect to researching similar projects and obtaining similar and applicable specifications to use as inputs; effort can take 2-3 days to find and obtain the data.
Generate Project Requirement Documents	80h..120h	Observation associated with the requirements development process on past projects in transforming needs to requirements for the system or product; effort can take 2-3 weeks to generate requirements.
Manually Assess Trace between Requirement Documents	20h..40h	Observation associated with prior analysis of looking at requirements, comparing to other documents and sources of data, discussion among team members; effort can take a half to a full week of effort among one or two personnel
Review Documents	20h..40h	Observation associated with performing reviews of several documents, including table top and email correspondence; effort can take a half to a full week of effort among multiple personnel
Publish Documents	20h..40h	Observation associated with personnel creating a finished document, applying appropriate markings, working with configuration management and obtaining all approvals; effort can take a half to a full week of effort among multiple personnel





Total hours for this process (Range of hours utilized for each task in the process)

Not evaluated – task time set to zero

Project SE Labor Costs from Requirement Quality and Quantity

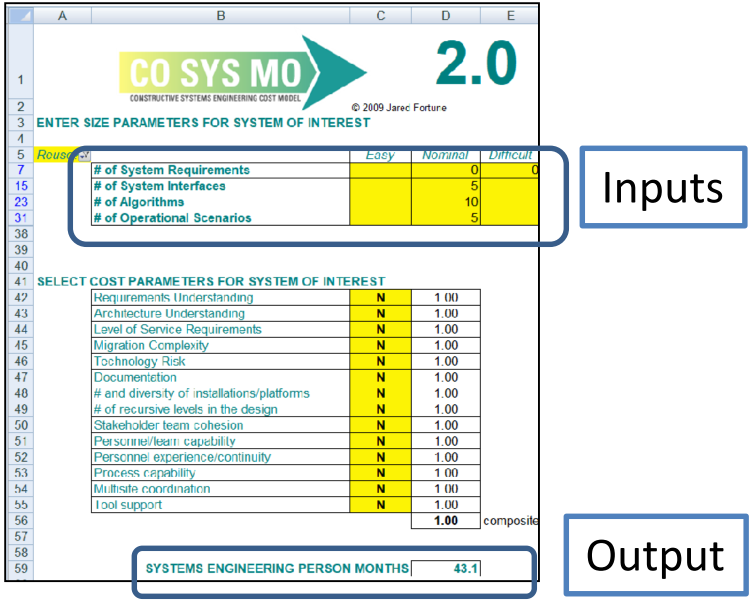
- The Constructive Systems Engineering Cost Model (COSYSMO) is a parametric model for estimating the systems engineering effort required for the development of space systems.
- COSYSMO can provide a predicted systems engineering labor in months based on inputs, which include requirement quantity and quality.
- Normalizing the non-requirement inputs, the requirement count for *easy*, *nominal* and *difficult* requirements are entered into the model and a resultant value for labor months can be obtained.
- Assessing *difficult* versus *nominal* requirements addresses cost associated with requirement **quality**, where the *count* is addressing cost associated with requirement **quantity**.

$$PM_{NS} = A \cdot \left(\sum_k \left(w_{e,k}\Phi_{e,k} + w_{n,k}\Phi_{n,k} + w_{d,k}\Phi_{d,k} \right) \right)^E \cdot \prod_{j=1}^{14} EM_j$$

Where:
PM$_{NS}$ = effort in Person Months (Nominal Schedule)
A = calibration constant derived from historical project data
k = {REQ, IF, ALG, SCN}
w_x = weight for “easy”, “nominal”, or “difficult” size driver
Φ_x = quantity of “k” size driver
E = represents diseconomy of scale
EM = effort multiplier for the j_{th} cost driver. The geometric product results in an overall effort adjustment factor to the nominal effort.

4 Size Drivers

1. Number of System Requirements
2. Number of System Interfaces
3. Number of System Specific Algorithms
4. Number of Operational Scenarios

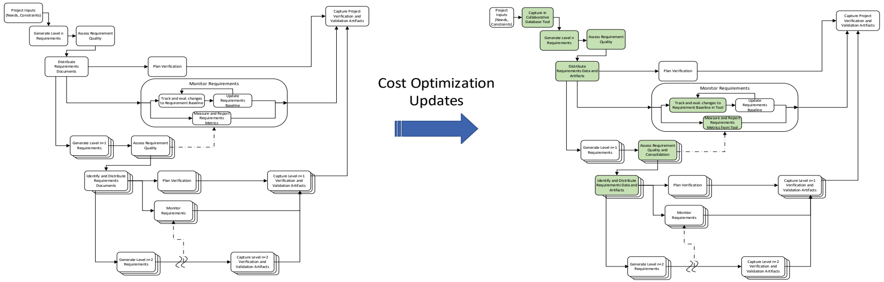


COSYSMO Cost Model. (Valerdi, 2010)

Generating Current State and Proposed Process Models

- Each of the four proposed process areas was researched to generate a current state approach as well as a proposed optimized approach .
  - Current state process flows are color coded yellow
  - Proposed optimized process flows are color coded green

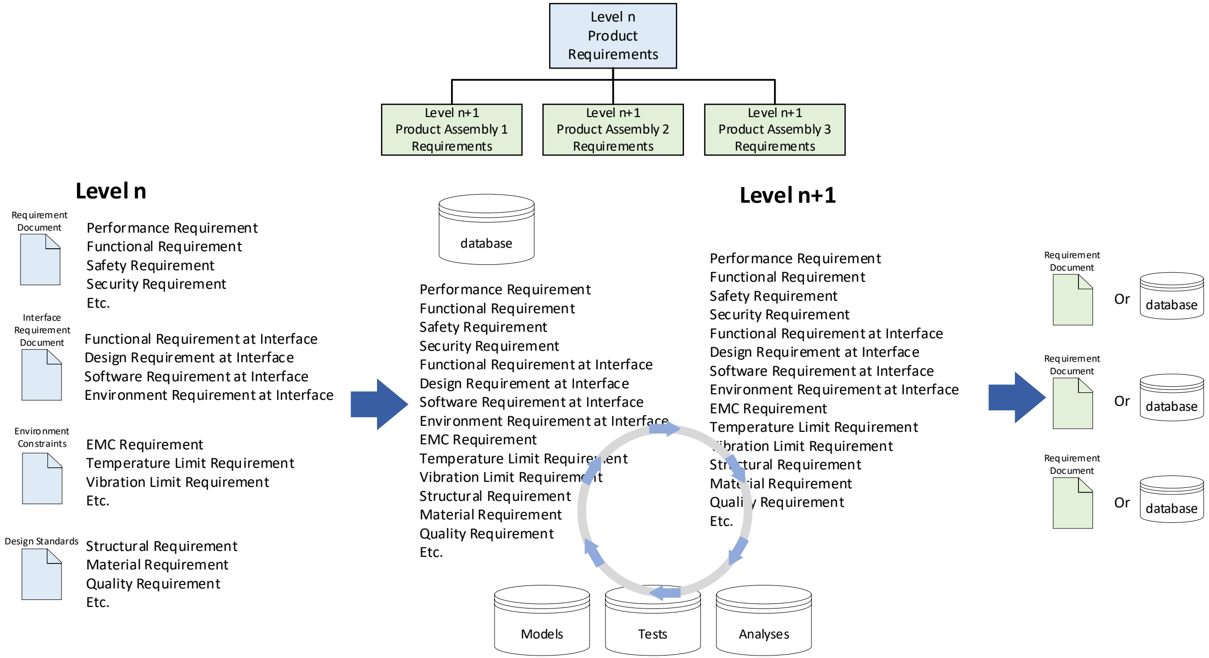
- The next set of slides show the flow diagrams for each process area, along with the factors used to measure costs associated with the process (labor time, COSYSMO, direct costs).



Current State Requirements Management Process Model

Optimized Requirements Management Process Model

Process Update 1 - Data Centric Requirements Management Approach

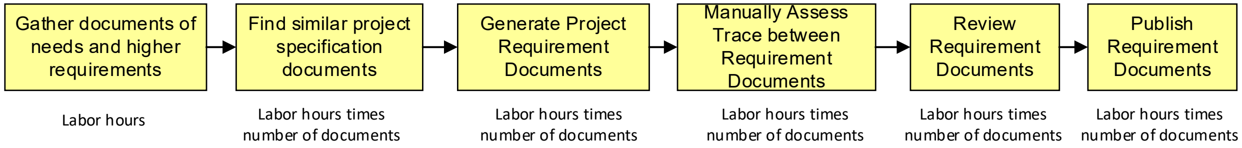


The “data centric” approach treats all requirements as a set of project data, compared to compartmentalized specification documents, enabling reduction in overlaps, closure of gaps, reuse of requirements at multiple levels, and trace to other project data.

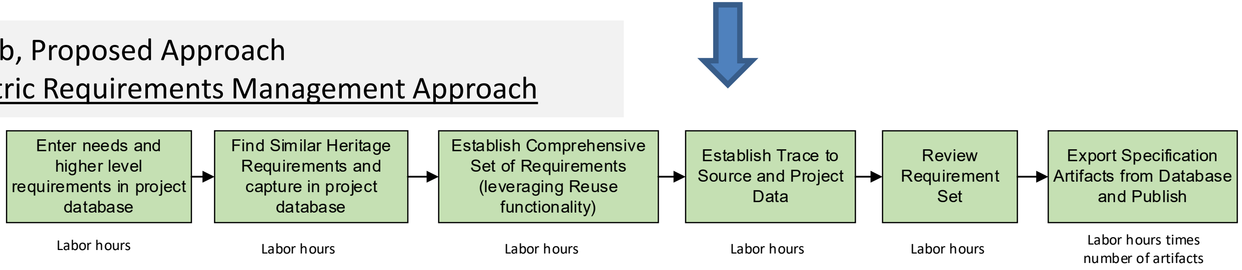
Process Update 1 – Data Centric RM Approach

- The data centric requirements management process uses labor hours per task as a comparison to the current state document centric approach.
- Any calculated savings can be compared with direct or labor costs of tools, changing processes and associated training.

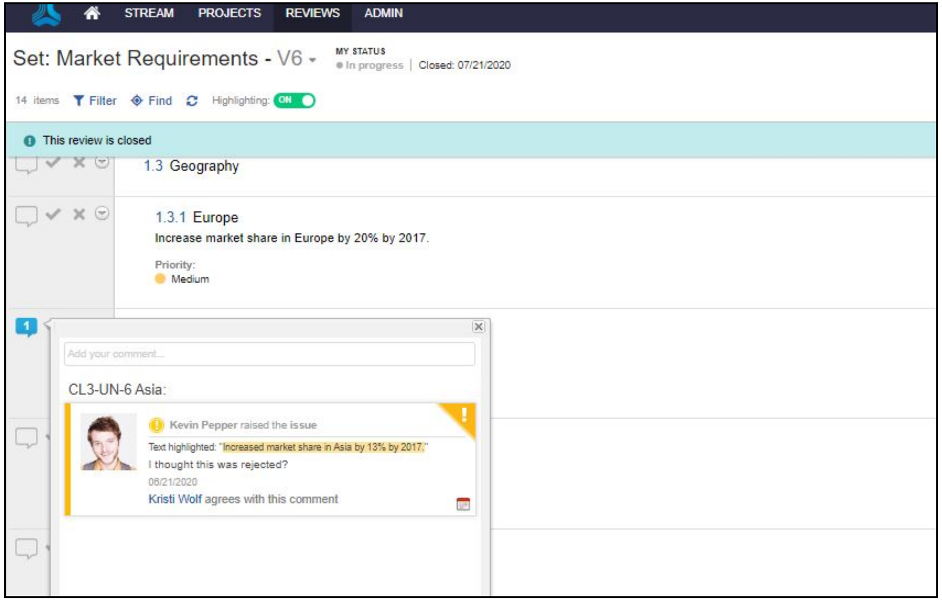
Process 1a, Current State
Document Centric Requirements Management Approach



Process 1b, Proposed Approach
Data Centric Requirements Management Approach



Process Update 2 – Usage of a Collaborative Requirements Management Tool

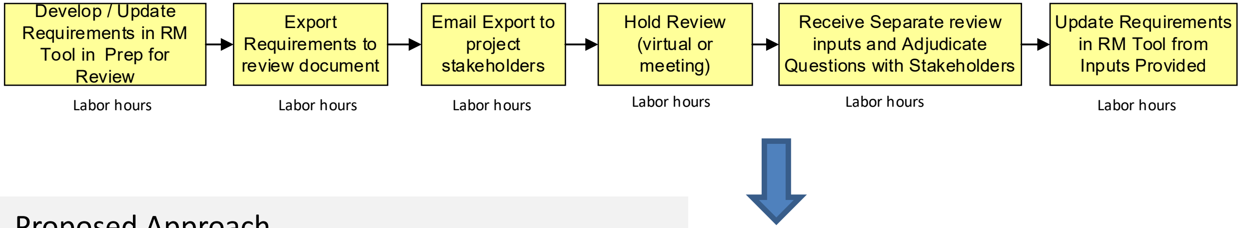


Usage of the collaborative requirements management tool enables all users to see the source of requirement data and trace, enabling the change process and reviews (compared to a subset of engineers interfacing with a specialized application).

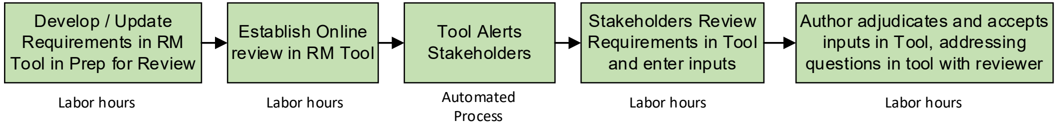
Process Update 2 – Collaborative Management Tool

- The processes associated with the use of a collaborative requirements management tool utilizes labor hours per task as a method to compare with the current state approach.
- Any calculated savings can be compared with direct costs of tool purchase and training activities.

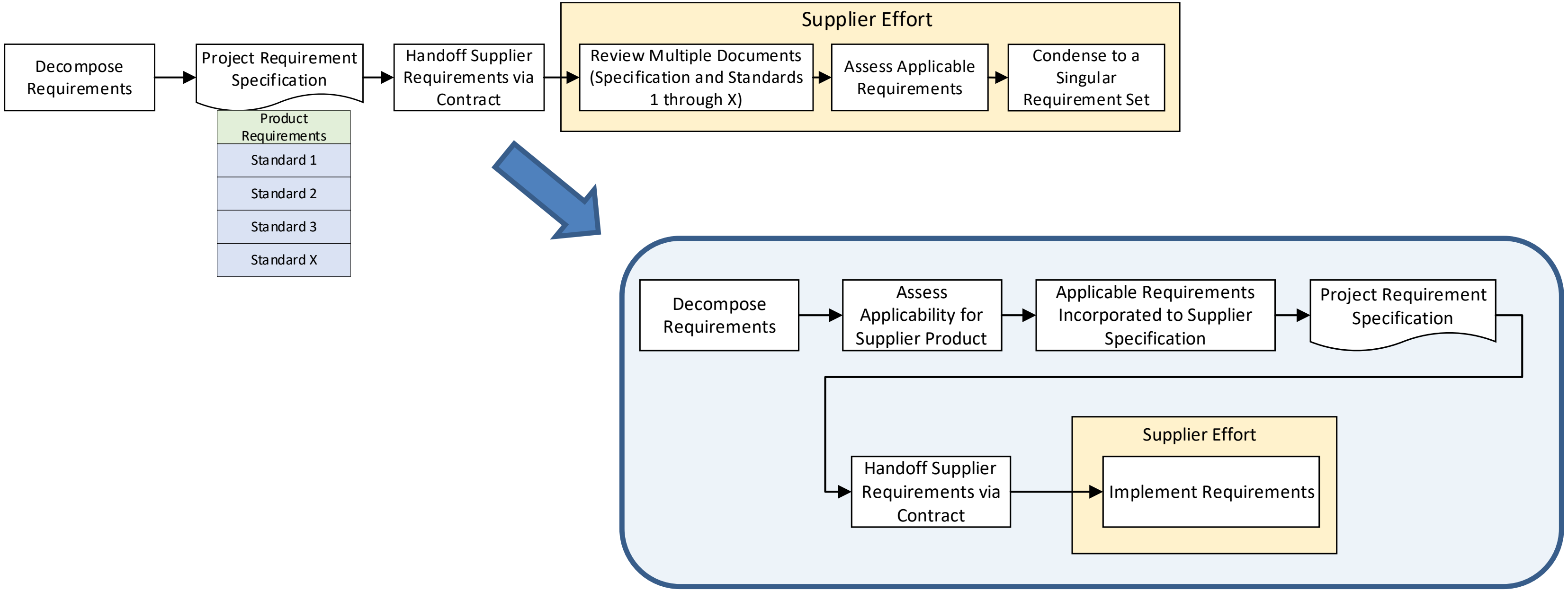
Process 2a, Current State
<u>Usage of a Non-Collaborative Requirements Management Tool</u>



Process 2b, Proposed Approach
<u>Usage of a Collaborative Requirements Management Tool</u>



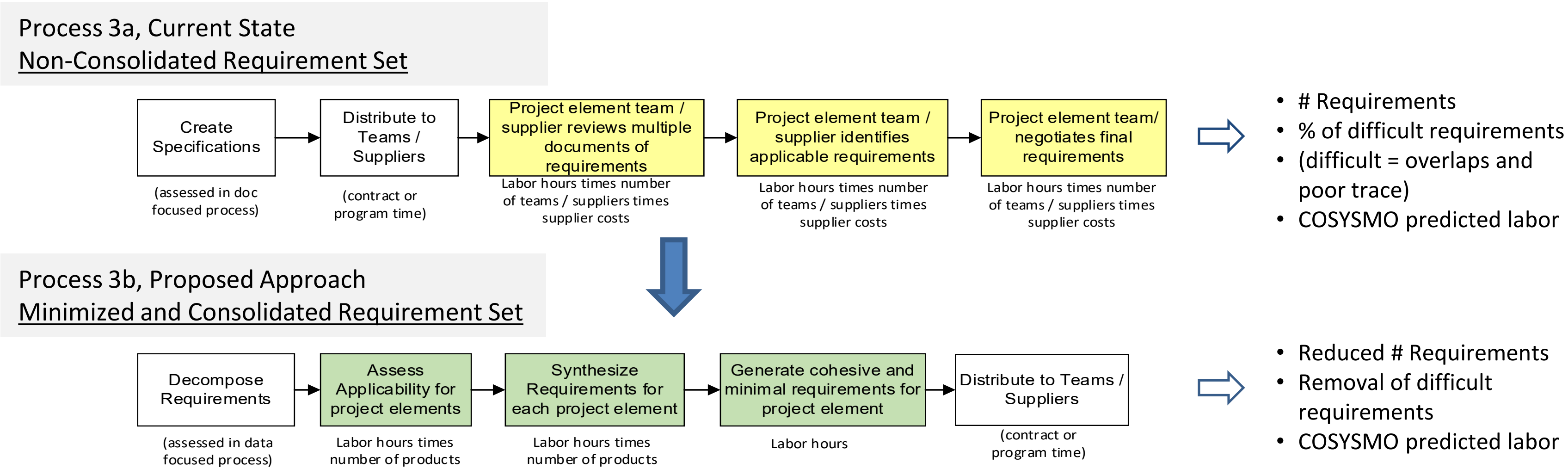
Process Update 3 - Minimize and Consolidate Requirements Approach



Spending up front time minimizing and consolidating the requirements for the lower levels enables reduction in overlaps, closure of gaps, removal of design mandates/constraint, and "just enough" requirements needing formal verification.

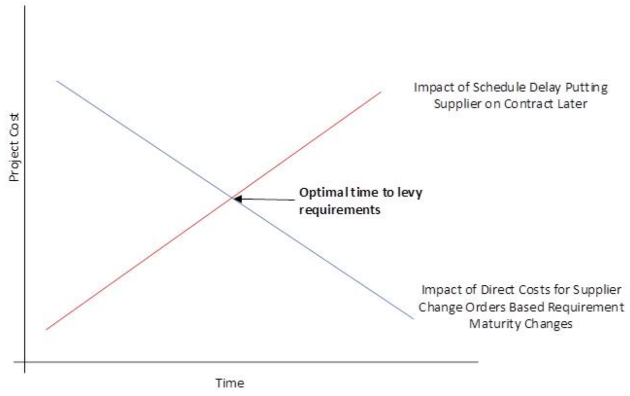
Process Update 3 – Minimize and Consolidate Requirements

- The requirement minimization and consolidation process uses labor hours per task as a method to compare with the current state approach. The current state effort is addressed by the design teams or suppliers, compared to the proposed process addressed by the systems team.
- Additionally, COSYSMO is used to estimate overall savings to the project in systems engineering labor based upon improvement of requirement quantity and quality.
- Any calculated savings can be compared with direct or labor costs of changing processes and associated training.
  - Note: The current state supplier costs in this study will be considered as labor costs for simplicity; this is a more conservative approach as direct costs will typically be more costly and skew the saving higher.



Process Update 4 - Evaluate Timing to Levy Unstable Requirements

- The process to assess timing of levying requirements on a supplier uses labor hours per task as a method to compare with the current state approach.
- Direct Costs are calculated associated with number of requirement change cycles levied on the supplier; this is an adjustable parameter based on the anticipated costs for the contract.
- The number of change costs is based on the requirement stability, which is calculated as the number of unresolved requirements (TBX) over the total number of requirements.
- For the optimized approach, the assessment of maturing the requirements to a more stable state before imposing is compared to the cost of any schedule impacts of delaying product delivery.



$$Requirement\ Instability\ Ratio = \frac{TBX\ Count}{Total\ Requirement\ Count}$$

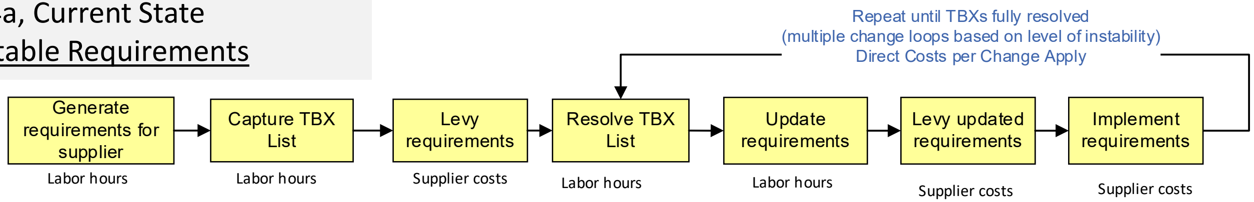
$$Total\ Change\ Costs = Change\ Count * Cost\ per\ Change$$

$$Change\ Count = Round\left[Instability\ Ratio * \left(\frac{1}{Change\ Size}\right)\right]$$

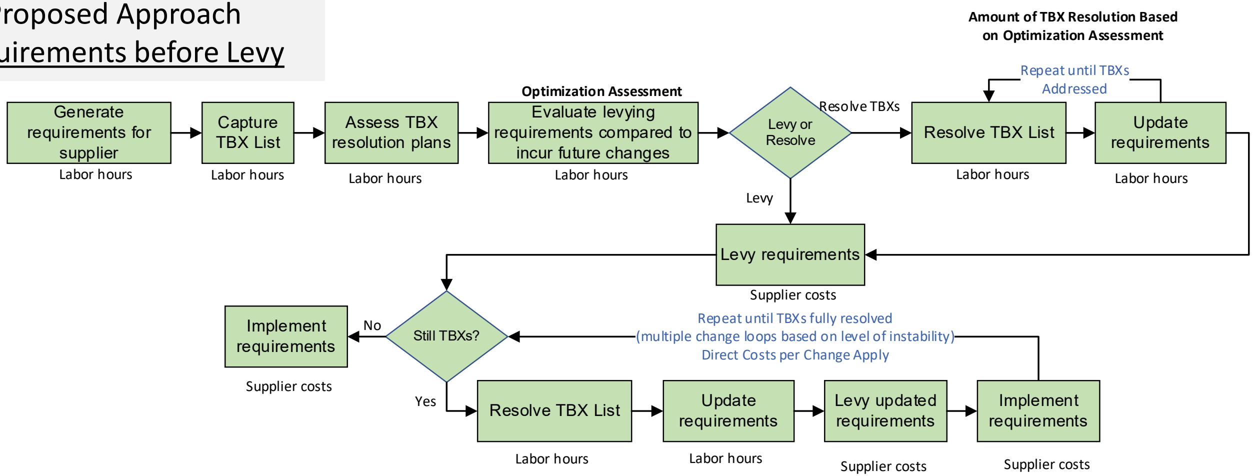
Spending time assessing *when* to formally levy requirements (considering actual need dates) enables requirement maturation and a reduction in supplier requirement change cycles.

Process Update 4 – Evaluate Timing to Levy Unstable Requirements

Process 4a, Current State
Levy Unstable Requirements



Process 4b, Proposed Approach
Stabilize Requirements before Levy



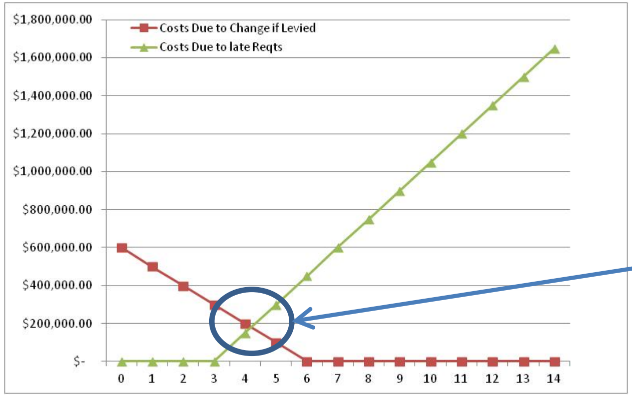
Excel Model: Direct Costs of Supplier Changes Using a Change Cost Optimization

- A change cost optimization model was developed for the dissertation to calculate an optimal point to levy requirements on a supplier.
- Inputs include requirement maturity stability (TBX/number of requirements), how much requirement maturity can be improved in a month, cost per change cycle, penalty cost per month if product is late, number of months until the product is needed, number of months it it takes to make the product.
- The Excel file generates linear equations for change cycle costs until requirements are mature, penalty costs associated with delay of product, and then calculates the optimal time to levy the requirements on the supplier (first order linear approximations are used for the purposes of comparison in this study).

Project Specific Inputs

	A	B	C	D	E
1	**Parameters**				
2	Cost/change	$ 100,000.00			
3	Starting Instability_ratio	0.6	change per month	0.1	
4	Duration to make	10	Change Count	6	
5	Product Needed	13			
6	Must Start	3			
7	Project Delay Costs/month	$ 150,000.00			
8					
9	**Month**	**Instability Ratio**	**Costs Due to Change if Levied**	**Delay**	**Costs Due to late Reqts**
10	0	0.6	$ 600,000.00	0	$ -
11	1	0.5	$ 500,000.00	0	$ -
12	2	0.4	$ 400,000.00	0	$ -
13	3	0.3	$ 300,000.00	0	$ -
14	4	0.2	$ 200,000.00	1	$ 150,000.00
15	5	0.1	$ 100,000.00	2	$ 300,000.00
16	6	0.0	$ 0.00	3	$ 450,000.00
17	7	0.0	$ -	4	$ 600,000.00
18	8	0.0	$ -	5	$ 750,000.00
19	9	0.0	$ -	6	$ 900,000.00
20	10	0.0	$ -	7	$1,050,000.00
21	11	0.0	$ -	8	$1,200,000.00
22	12	0.0	$ -	9	$1,350,000.00
23	13	0.0	$ -	10	$1,500,000.00
24	14	0.0	$ -	11	$1,650,000.00
25					
26	y=mx+c, x=(y-c)/m	m	c		
27	slope/intercept change cost	-100000	600000	1	
28	slope/intercept late costs	150000	-450000	2	
29					
30	**Optimal Time to Levy**	**Supplier Change Costs**	**Instability Ratio**	**Supplier Chg Count**	**Internal Change Count**
31	4.2	$ 200,000.00	**0.18**	**2**	**4**

Outputs



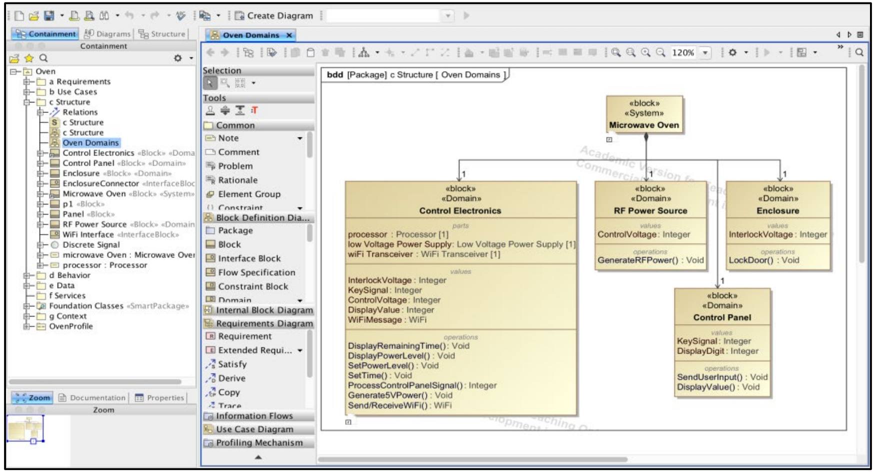
Need for an Executable Model

- After developing process diagrams and Excel models there was a need to generate analytical capability to assess the different processes.

- While Excel might have been able to show duration calculations over multiple iterations, it does not have the graphical nature to represent varying process flows and value changes.

- Systems Modeling Language (SysML) is a graphical modeling language used to visualize and communicate designs of systems consisting of hardware, software, data, people and processes.

- It was determined that a SysML simulation would be used to show individual process models, connect them to generate an overall Requirements Management model, and utilize the capabilities of the modeling tool to calculate duration of the processes and parameters related to change costs.



SysML Model Example

PROCESS MODEL SIMULATIONS AND RESULTS

Generation of a Requirements Management Model

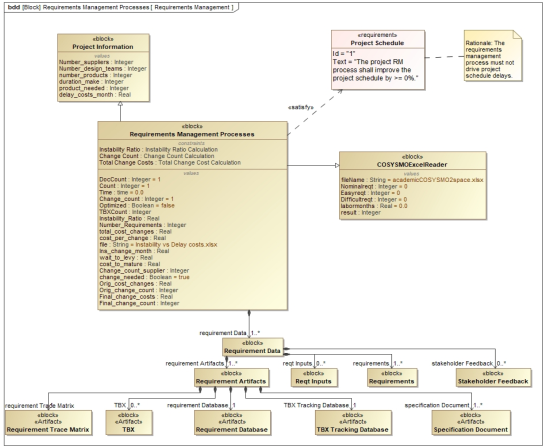
- A requirements management process model was created in Cameo Systems Modeler by No Magic/Dassault, using their Cameo Simulation Toolkit and Excel Import plugins.

- The requirements management process relationships and associations were shown on a block definition diagram.

- The four current state/proposed processes were modeled as activity diagrams.

- An overall requirements management activity diagram was modeled as an activity diagram, using the individual process diagrams within it, and contains a path selection for optimized (true or false).

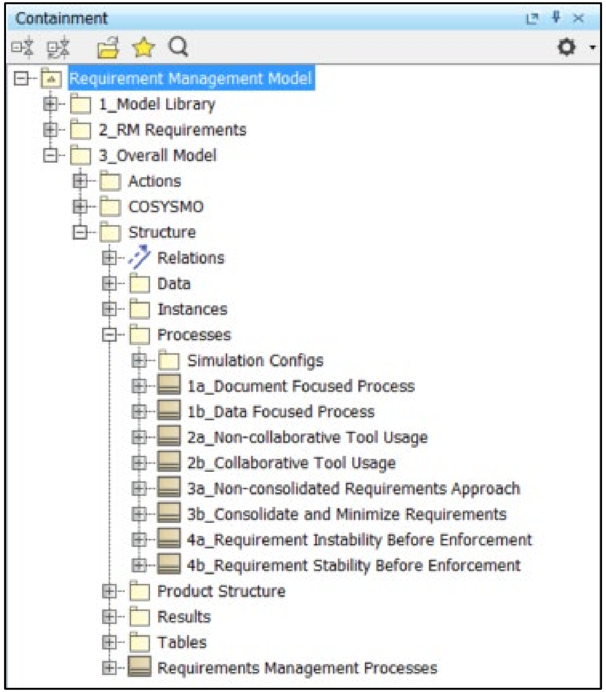
- Simulations of the individual model were conducted over a range of inputs, resultant data was written to an instance table and then analyzed for trends. The overall Requirements Management (RM) model was simulated with data from past NASA projects to assess how the overall Requirements Management approach would trend with actual project performance.

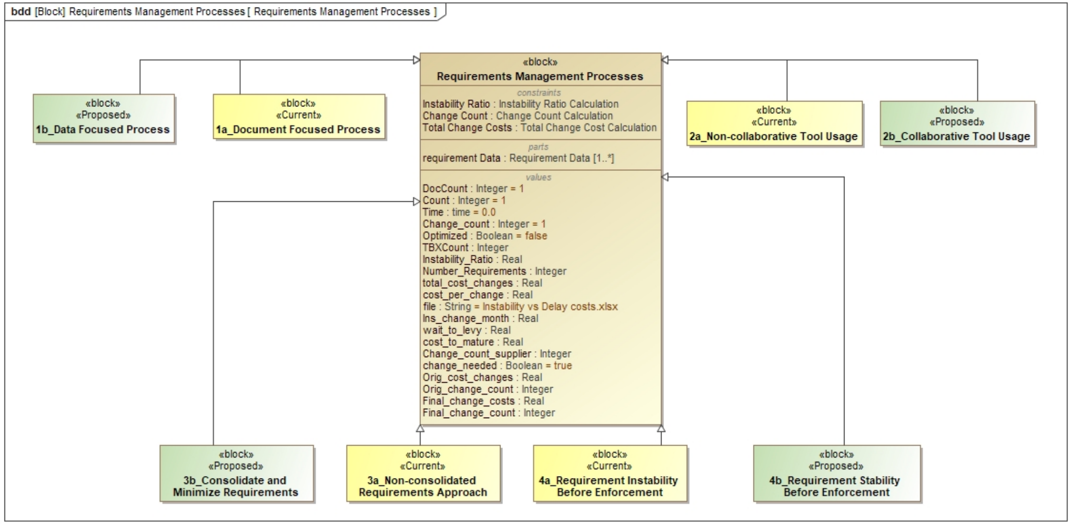


The following slides highlight the details of the model, the simulation effort, and the resultant data. A more in depth presentation is available on the INCOSE RWG YouTube Channel: https://youtu.be/kkyGzHWB1vU

RM Model Content

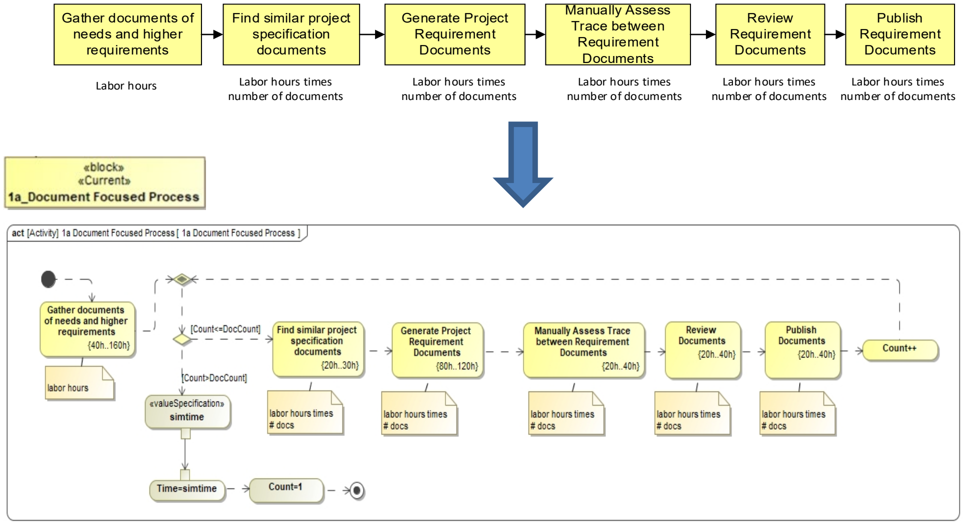
- The organization of the model focused on the processes, showing them as blocks and behavior elements.

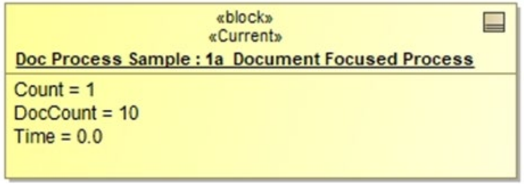




Process 1a SysML Model Overview

- Process 1a was modeled as an activity diagram using duration constraints to represent a minimum and maximum time to perform a task.
- Inputs are provided using an “instance” assignment for parameters within the process block shown on the prior slide.
- The value for number of documents (DocCount) prompts a repeat of several steps of the process.
- The duration time (simtime) is assigned to the parameter Time, which is reported in a data table after each simulation is executed.



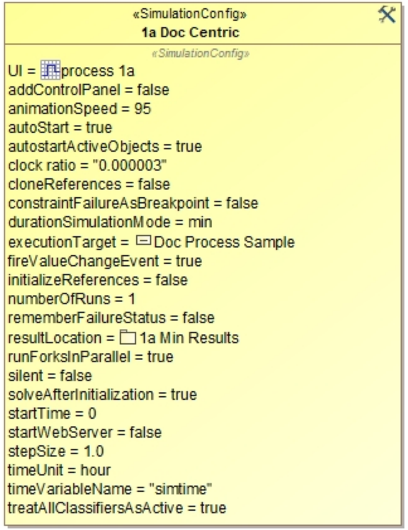


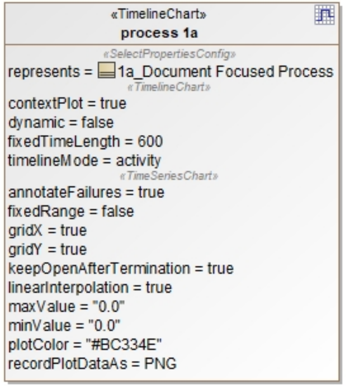
Process 1a Simulation Configuration

- A simulation configuration was created to assign the parameters used in the process 1a simulation.
  - The execution target is set to the process 1a instance, which calls the activity diagram for that process.
  - The clock ratio is set to 0.000003, which speeds up the simulation to much faster than real time.
  - The result location is a folder that captures the resultant instances created during the simulation, these instances show the value parameters at the time of simulation and the resultant value of Time.
  - Simulation start time is set to 0 (allowing the ‘timer’ to start at the beginning of the simulation), and units are set to “hour”.
  - The simulation time variable is established as “simtime”.

- The activity tasks were set to a possible range of values, allowing the simulation to be run at the different ranges; the *durationSimulationMode* is set to use either the minimum times, maximum times, average times, or a random set. For the process simulation these were adjusted between min and max.

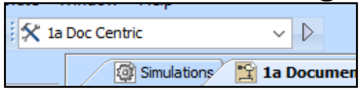
- A Timeline chart was made and added to the simulation as a UI parameter, allowing a graphical look of the durations as the simulation was executed.

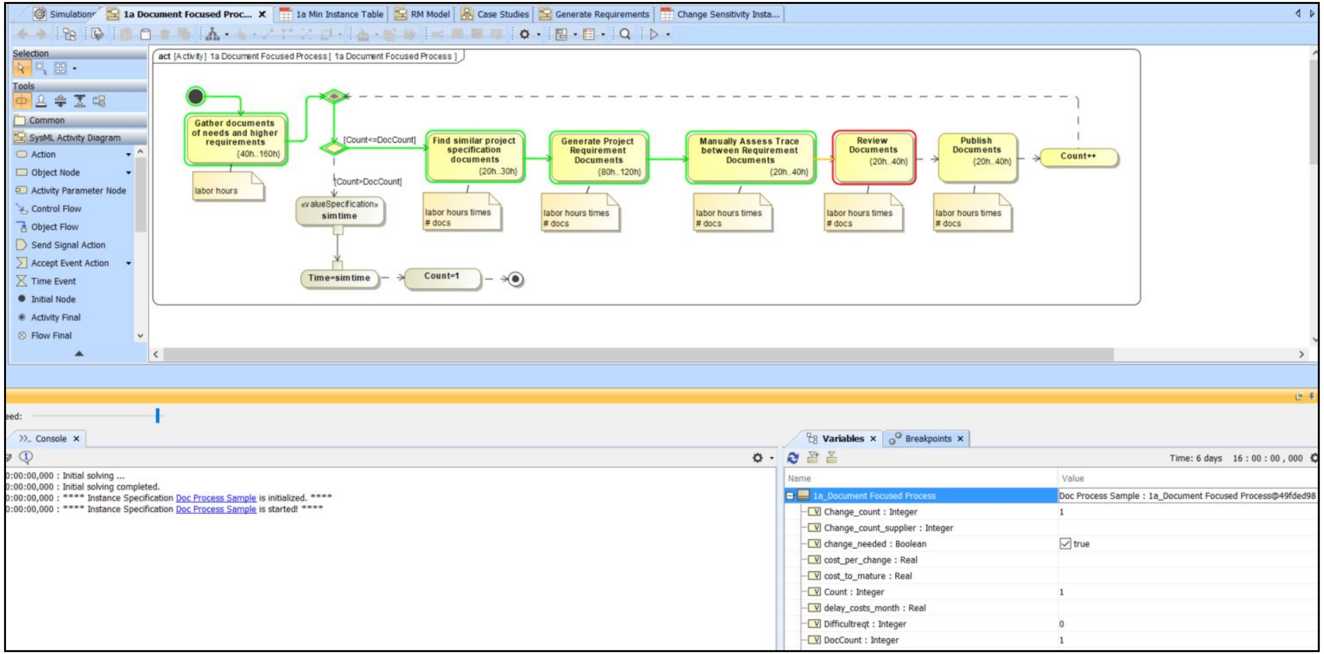




Process 1a Simulation Run

- Selecting the simulation configuration name and the run icon starts the simulation for process 1a.
- The activity diagram visually shows the location of the simulation during the execution, and the value parameters are updated in the Variables tab.

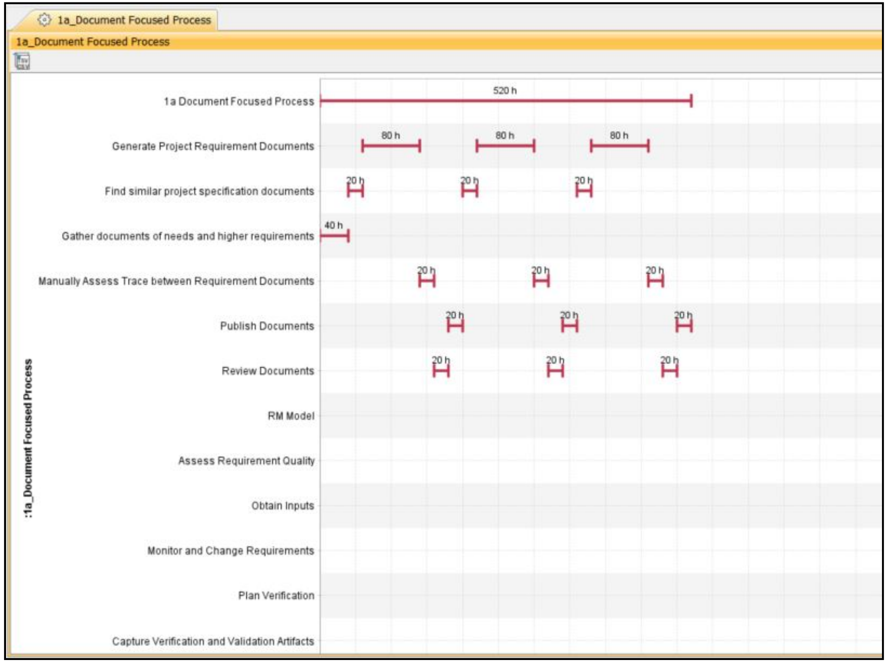




Process1a Sim.mp4

Process 1a Simulation Run (cont.)

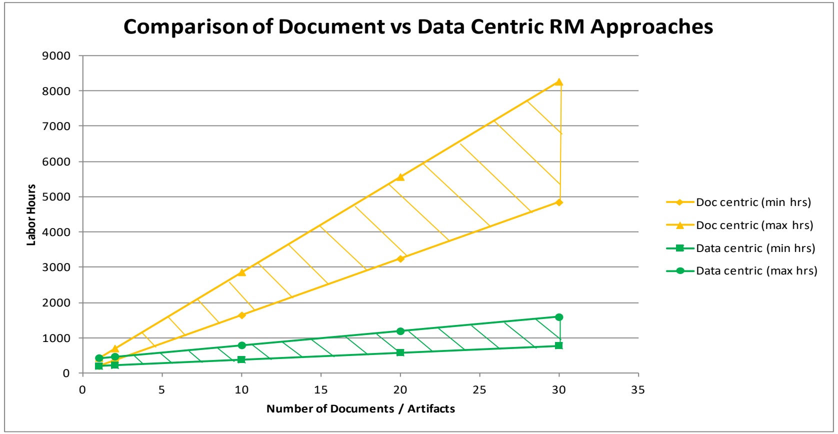
- During the run the Timeline chart shows the durations for each action in the activity diagram.



Process 1a Instance Table and Data Results

- An instance table was developed that showed the starting instance block and simulation results created in the results folder.
- For every run performed a new value would appear in the table.
  - The minimum duration simulations were reported in a different instance table from the maximum duration simulations.
- After running the simulation for process 1a and 1b at minimum and maximum durations, the data was exported and graphed further in Excel to analyze for trends.
  - Note: The Process 1b simulations were identical, the associated activity diagram is shown in the Backup.

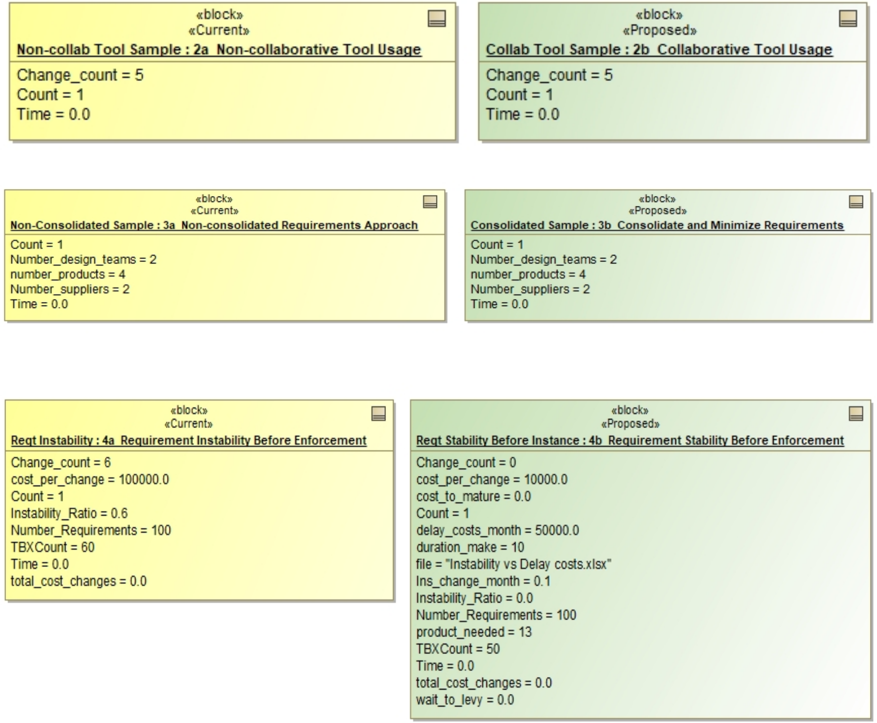
#	Name	DocCount : Integer	Time : time
1	Doc Process Sample	1	0
2	1a_Document Focused Process at 2021.01.17 14.04	1	200
3	1a_Document Focused Process at 2021.01.17 14.05	2	360
4	1a_Document Focused Process at 2021.01.17 14.06	10	1640
5	1a_Document Focused Process at 2021.01.17 14.06	20	3240
6	1a_Document Focused Process at 2021.01.17 14.07	30	4840



Range of Labor Hours for Process 1 Current State and Optimized based on Total Document Count

Process 2-4 Simulations

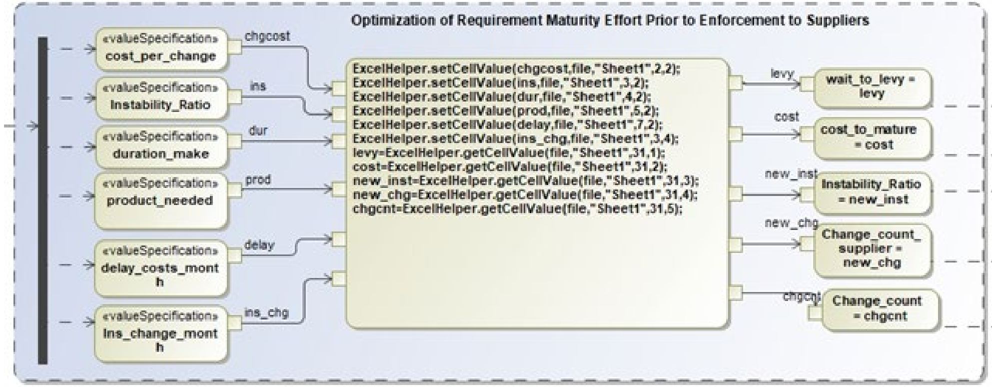
- Process 2, 3 and 4 simulations were conducted in a similar manner. Activity diagrams are shown in Backup.
- Process 2 varied the value of change count during the activity.
- Process 3 varied product count, as well as the number of design teams and suppliers making the products (supplier time is not equivalent to design team time, it is increased due to less familiarity with the product and requirements).
- Process 4 calculated the instability ratio and resultant change count from number of TBXs and number of requirements, and varied the inputs over a range of instability ratios.

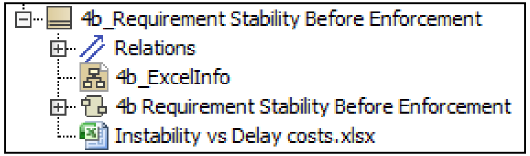


Process 4b Excel Integration

- Process 4b invoked the Change Cost Optimization Model Excel file named “Instability vs Delay Costs”, supplying values for inputs and extracting the values for outputs.

- This activity simulation resulted in data for direct costs associated with change cycles based on requirement maturity level, as well as data on the optimal time to wait to levy the requirements on the supplier to minimize overall costs.



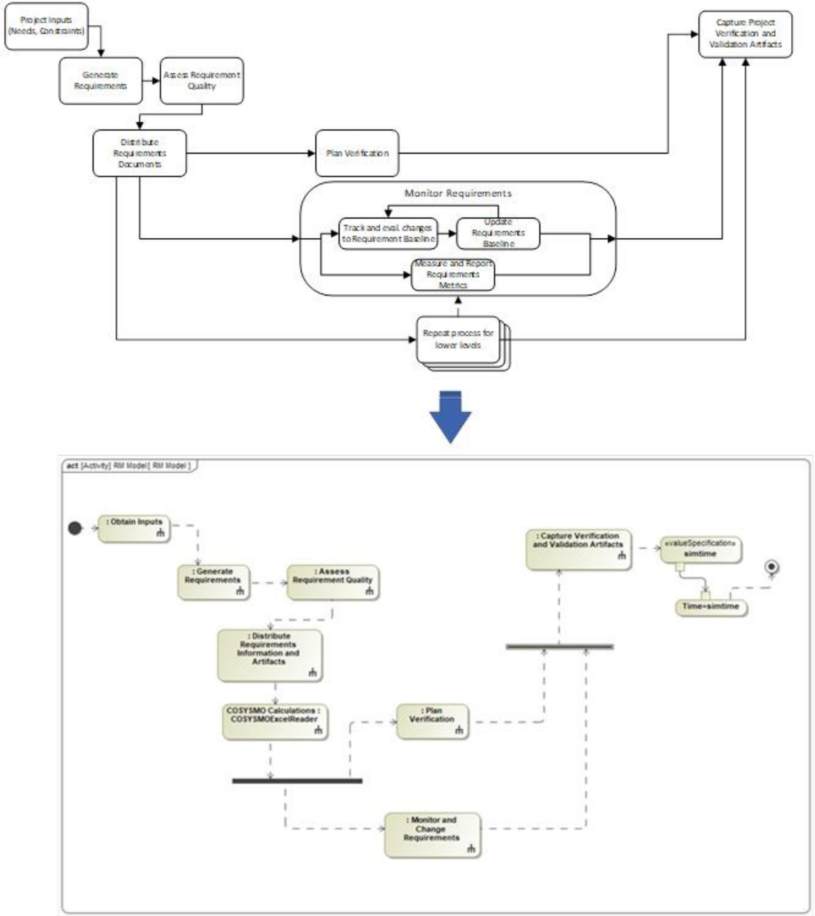


	A	B	C	D
1	**Parameters**			
2	Cost/change	$ 100,000.00		
3	Starting Instability_ratio	0.6	change per month	0.1
4	Duration to make	10	Change Count	6
5	Product Needed	13		
6	Must Start	3		
7	Project Delay Costs/month	$ 150,000.00		

30	**Optimal Time to Levy**	**Supplier Change Costs**	**Instability Ratio**	**Supplier Chg Count**	**Internal Change Count**
31	4.2	$ 200,000.00	**0.18**	**2**	**4**

Overall RM Model

- For the overall model, an activity diagram showing the requirements management process was developed with connected lower level activity diagrams invoked within the actions.
- This model additionally brought in the COSYSMO Excel file to calculate systems engineering labor hours.
- This model incorporated the process 1-4 models, the simulation provided data on labor hours associated with the requirements management processes, SE Labor time to the project, and direct costs for change cycles.

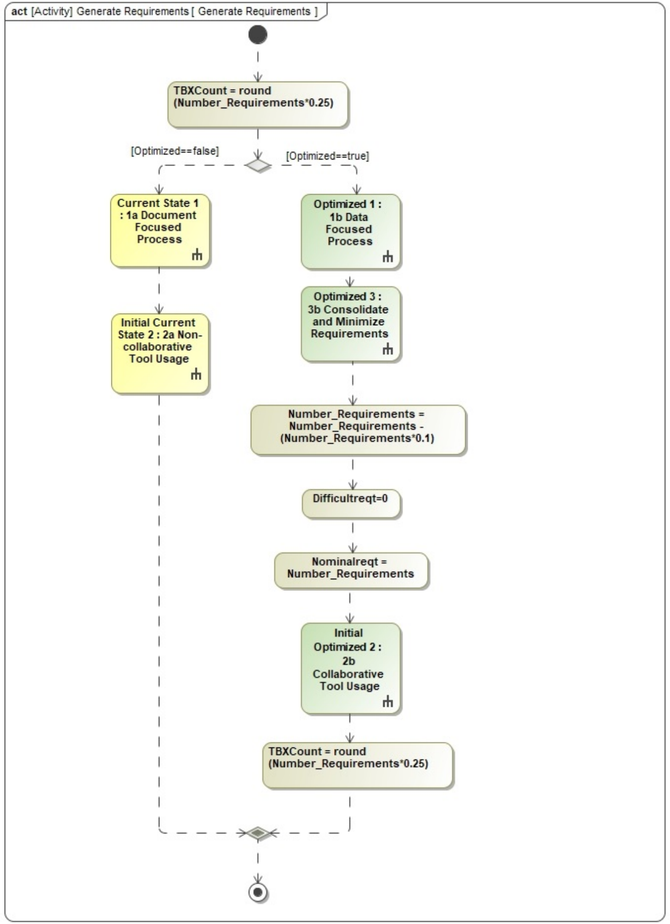


Optimized or Current State Paths

- The RM Model utilizes user input to choose an optimized approach or the current state approach (setting Optimized to true or false).

- This model also utilizes Opaque Actions to calculate updated parameters based on option chosen. Example: using the Optimized Consolidation Process 3b reduces the requirement quantity by 10% and removes overlaps (changing to all nominal requirements for COSYSMO) . This value was selected as a minimum level of improvement, there is likely a higher percentage of improvement with the process in a real world application.

- For this assessment either all current state or all optimized processes are chosen; future simulations could be done to mix and match approaches. Based on data from the process 1-4 it is expected that usage of ANY of them will yield cost benefits compared to the current state.



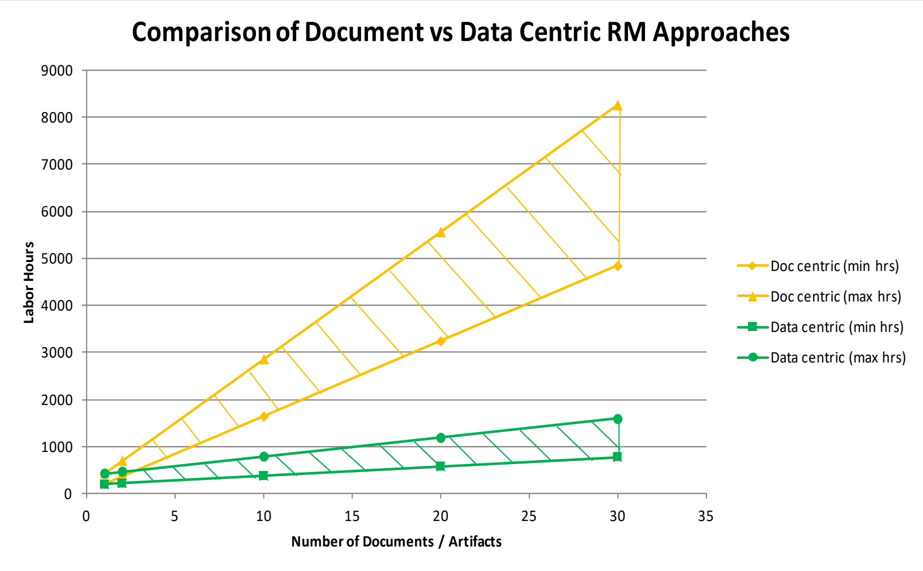
RESULTS

Process 1 – Data Centric RM Approach Results

- The results of this simulation provides the project with data to assess whether the project should invest in pursuing a particular process method.

- The results of process 1 simulation shows in cases where there is a high number of requirement documents there is a cost savings associated with a data centric requirements management approach.

- There may be less benefit of implementing the approach for projects that have very few requirement documents (small products with fewer requirements, as example).



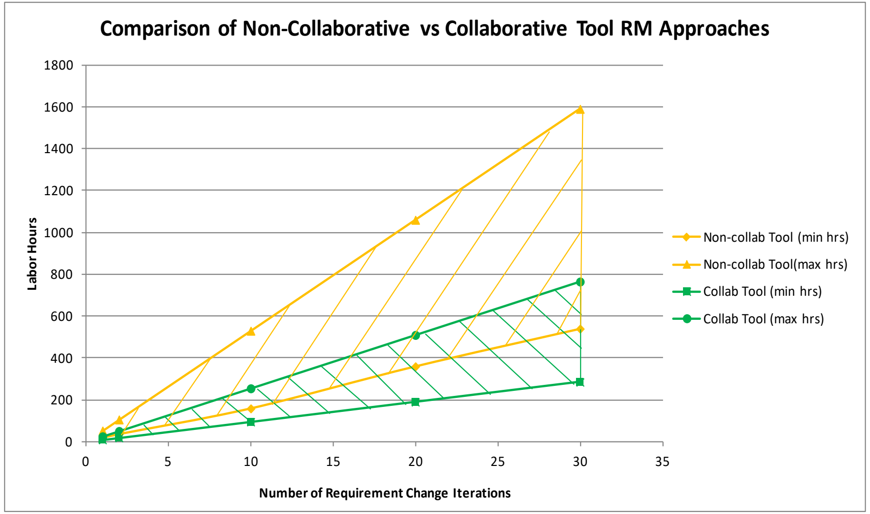
Range of Labor Hours for Process 1 Current State and Optimized based on Total Document Count

Process 1 shows cost benefits for projects with a large number of specifications and standards.

Process 2 – Collaborative Management Tool Results

- Results from process 2 simulation shows that in cases where the project has many requirements with a high level of development, cost savings could be realized compared to a comparable project using a non-collaborative requirements management tool.

- The aspect of this process that is more difficult to model is the requirement quality associated with each process.
  - While the labor savings may be less compared to the prior section in using the new approach, the input from the requirements management experts noted a clear benefit to the requirement quality when multiple users are in the tool developing the requirements together.
  - Case studies of Jama Software customers revealed that implementing a structured collaboration in the requirements management tool saved $150,000 per project, and planning time for requirements took 20% of the time it used to in legacy approaches (Jama Software, 2020).

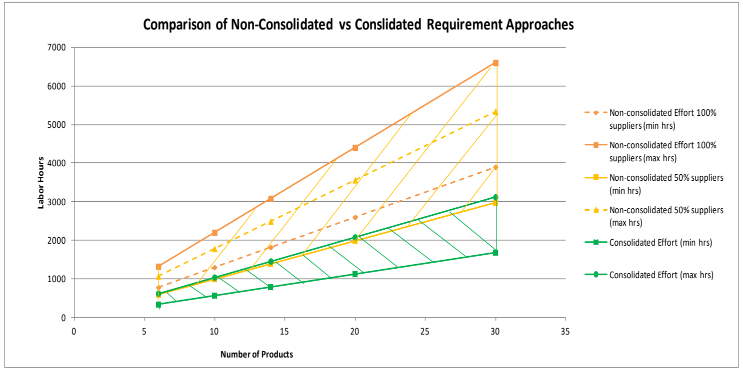


Range of Labor Hours for Process 2 Current State and Optimized based on Requirement Change Count

Process 2 shows some cost benefits for projects a large number of requirements change cycles.

Process 3 – Minimize and Consolidate Requirements Results

- Results from process 3 simulation shows that:
  - There is an substantial labor cost associated with efforts to consolidate the requirements with a larger number of products (right side of the table below).
  - There is also a larger cost associated with having the suppliers do the effort of consolidating requirements levied on them (left side of the table).
  - If the entire development effort was done in-house, there does not seem to be an obvious benefit to having the systems engineering organization consolidate requirements at the system or product level.
- The next slide provides breakout of costs for a system with a large number of products, as well as additional costs associated with COSYSMO estimated Systems Engineering labor from the model.



	Non- consolidated								Consolidated	
# Products	100% suppliers (min hrs)	100% suppliers (max hrs)	80% suppliers (min hrs)	80% suppliers (max hrs)	50% suppliers (min hrs)	50% suppliers (max hrs)	100% design teams (min hrs)	100% design teams (max hrs)	SE Labor (min hrs)	SE Labor (max hrs)
6	780	1320	718	1236	594	1068	408	816	336	624
10	1300	2200	1176	2032	990	1780	680	1360	560	1040
14	1820	3080	1634	2828	1386	2492	952	1904	784	1456
20	2600	4400	2352	4064	1980	3560	1360	2720	1120	2080
30	3900	6600	3528	6096	2970	5340	2040	4080	1680	3120

Range of Labor Hours for Process 3 Current State and Optimized based on Number of Products and Percentage Developed by Suppliers or In House

Process 3 shows cost benefits for projects a large number of products developed by suppliers for task durations.

Process 3 – Minimize and Consolidate Requirements Results

- The first table presents the cost savings with having the systems engineering team at the system level perform an assessment and refinement of the lower level requirements for 30 products, where the project will net an overall savings regardless of work done in house or by suppliers.
  - Assuming one labor month contains 160 hours (an upper bound with four entire weeks in a month), the costs in labor month to address 30 products is provided.
  - The cost of systems engineering labor to address applicability and consolidate and minimize requirements for 30 products is less than the cost of the suppliers undertake this effort (typically concurrent activities), or in-house design teams.

- With respect to outcome of the effort due to improvement of requirement quantity and quality, the second table provides the systems engineering costs of the requirement activity (in labor months) along with the associated savings from COSYSMO for reducing the product requirements quantity and overlaps by 10%.

Task Labor Hours for Consolidating for Ten Products

Activity	Duration (months)	Comment
Maximum labor time of SE consolidating and minimizing at system level for ten products	7	Labor cost to consolidate requirements
Versus...		
Maximum labor time for ten suppliers to address non-consolidated requirements	14	Supplier cost resulting from non-consolidated requirements
Maximum labor time for ten Design teams to address non-consolidated requirements	9	Design team cost resulting from non-consolidated requirements

COSYSMO Return on Investment for Consolidating and Minimizing 200 Requirements

Activity	Duration (months)	Comment
Maximum labor time of SE consolidating and minimizing at system level for ten products	7	Labor cost to consolidate requirements
Yields....		
Minimization only option: Resulting effort reduces requirements by 10%	-8	Project labor savings if 200 requirements reduced by 10%
Minimization and Consolidation: Resulting consolidation goes from 20 difficult, 180 nominal requirements to 180 nominal only.	-30	Project labor savings if 200 requirements reduced by 10% and no difficult requirements remain.

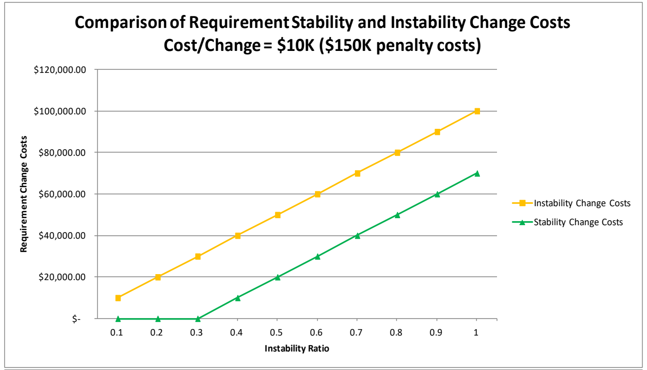
Process 3 shows cost benefits for overall project systems engineering labor based on requirements quality and quantity improvements.

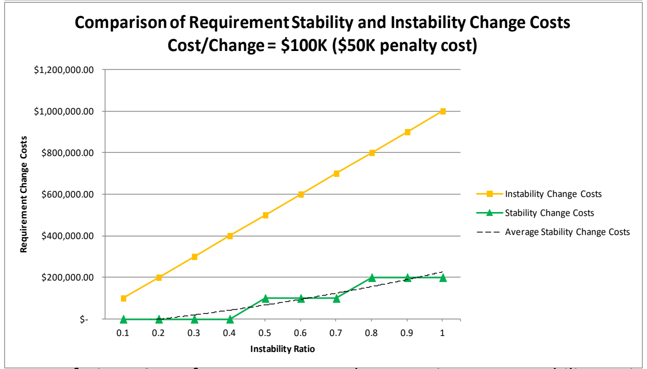
Process 4 – Evaluate Timing to Levy Unstable Requirements

Results

- The durations of current state and proposed processes for addressing requirement maturity were similar.

- The direct costs associated with supplier change costs is where the proposed process appears to add value, particularly in cases where there is a high cost per change and low delay penalty cost.





Range of Direct Costs for Process 4 Based on Requirement Instability Ratio

Process 4 shows cost benefits for direct costs of supplier changes for cases of high change costs and lower schedule penalty costs.

Benefits of Proposed Process Updates

- Each of the four proposed process updates individually demonstrated improvement against more traditional approaches.

- Adding any of these recommendations to a project's requirements management effort could be beneficial when compared to the specific application and costs to implement.

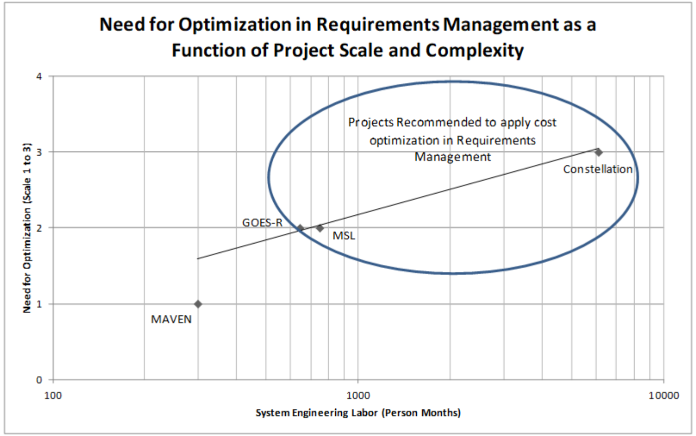
- The next section will highlight demonstration of applying all four using a set of simulations with the NASA space project inputs.

✓**Hypothesis**: Each of the four recommended approaches will provide cost optimization over current approaches, enabling selection of process improvement options for programs to apply.

Prior NASA Space System Examples

- Research into past NASA programs was done for products ranging in complexity (resource, product and requirement scope) from moderate to high.
- Based on the results of the research each project was assessed against their approach to requirements management, success of the project, and assessment of need for a more optimized approach.
- The parameters from these projects are used to compare potential optimization methods against the more traditional methods utilized by these projects – the results of this are provided later in the presentation.

Project	# of System Requirements	Estimated SE Labor (Person Months)	Project Notes	Need to Optimize Requirements Management (1-3)
MAVEN	660 (0 of these are rated difficult)	298	Successfully executed project objectives	1
MSL	511 (309 of these are rated difficult)	747	Project was moderately successful, further optimization could have ensured it met cost and schedule objectives.	2
GOES-R	~1300 (50 of these are rated difficult)	643	Project was moderately successful, further optimization could have ensured it met cost and schedule objectives.	2
Constellation	~8600 (1220 of these are rated difficult)	6109	Project Cancelled in Design Phase	3
Artemis HLS	~4551 (460 of these are rated difficult)	2802	Project Still in Development	Cannot rate



NASA project research demonstrated a trend of project success variation as a function of complexity

RM Model Simulation Configuration

- The RM Model reflects an overall process for a project, using actual data from past space projects in the simulation.
- Instance blocks were created to provide inputs for each project.
- Unknown information was either normalized, or used as the variable parameters for three case study runs of the simulation.
- Each Case Study simulation varied a parameter for the space projects to evaluate impacts to the requirements management process simulation results.
  - Case Study 1 used 25% Instability Ratio, Low Change Costs
  - Case Study 2 changed to 50% Instability Ratio
  - Case Study 3 changed to High Change Costs

Space Project Actual Data

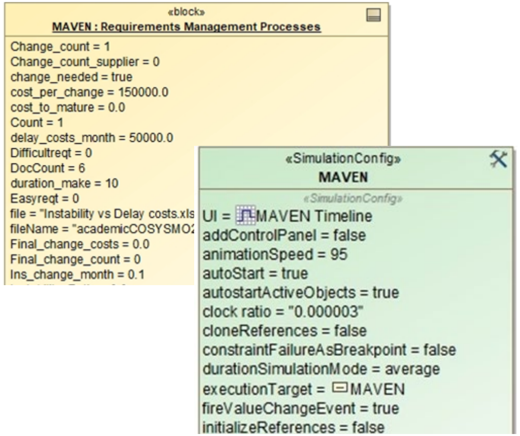
Project	# of System Requirements	Number of Documents	Number of Suppliers	Number of Internal Design Teams
MAVEN	660 (0 of these are rated difficult)	6	6	0
MSL	511 (309 of these are rated difficult)	1	12	22
GOES-R	~1300 (50 of these are rated difficult)	11	9	0
Constellation	~8600 (1220 of these are rated difficult)	51	4	1
Artemis HLS	~4551 (460 of these are rated difficult)	46	1	0

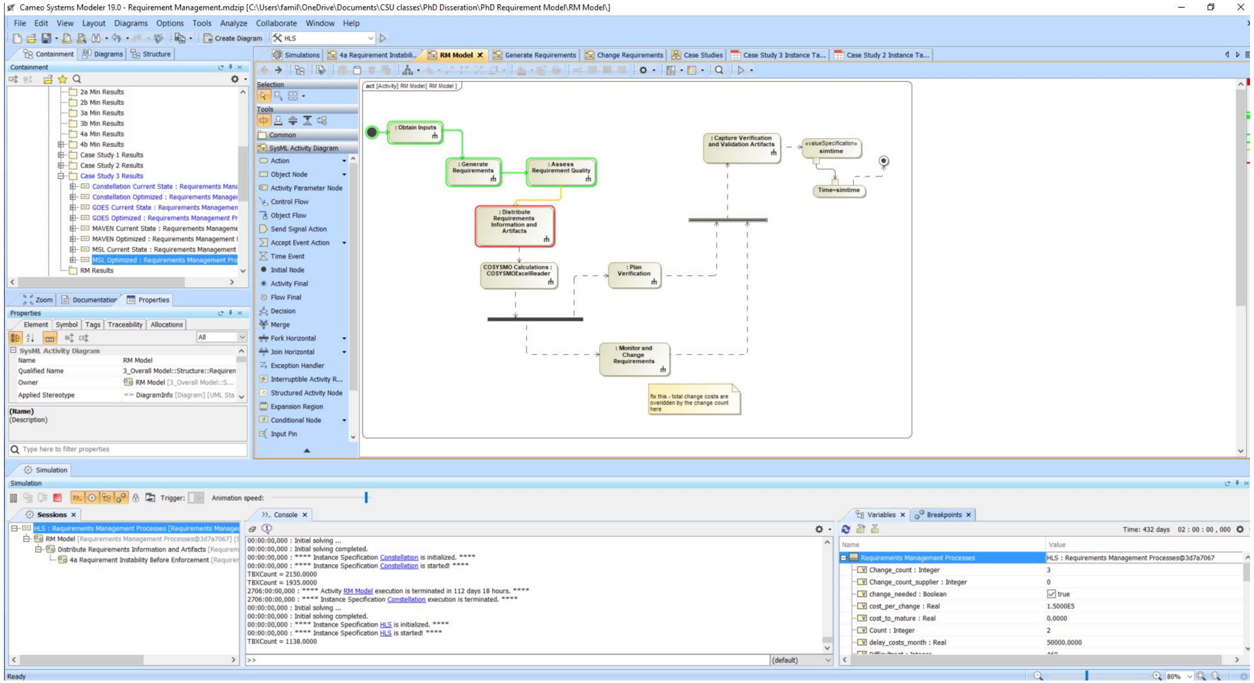
Space Project Assumed Inputs and Case Study Parameter Variation

Parameter	Case Study 1	Case Study 2	Case Study 3
TBX Count (% of requirements)	25%	50%	25%
Duration to Make	10 months	10 months	10 months
Product Needed	13 months	13 months	13 months
Delay Costs per Month	$50,000	$50,000	$50,000
Costs per Change	$75,000	$75,000	$150,000
Instability ratio change per month	0.1	0.1	0.1

RM Model Simulations

- Just like the individual process simulations, the RM Model simulation for the space projects was executed and data captured to an instance table, yielding results that were further analyzed.

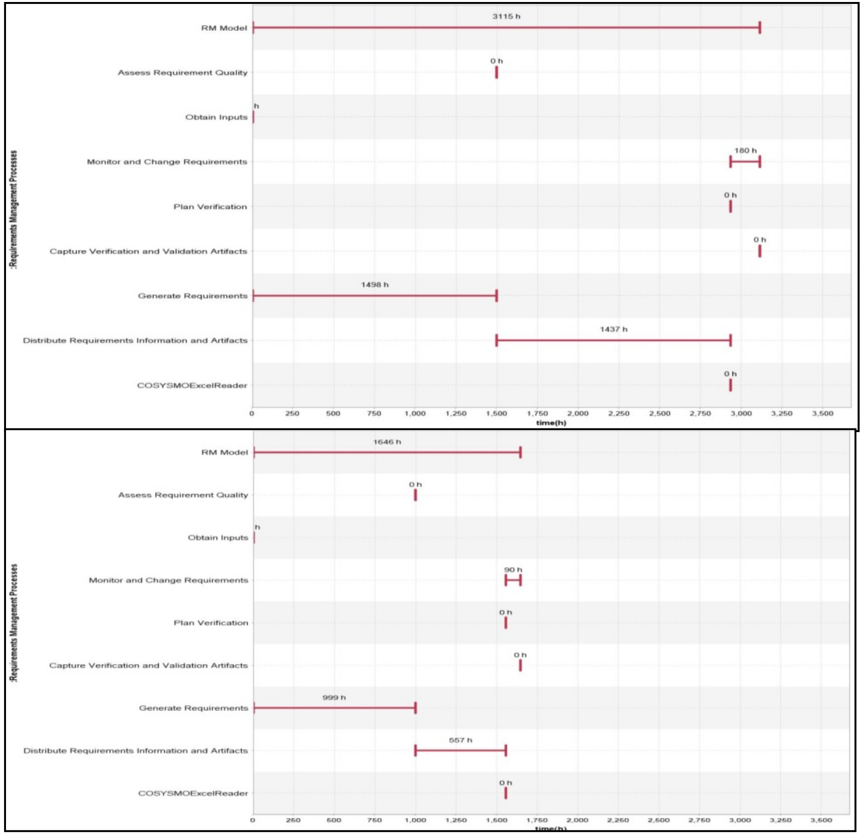




Space Project Case Study Simulation Results

- Timeline chart showing the overall process durations with the current state and optimized approaches on MAVEN.

MAVEN Case Study 1 Current State and Optimized RM Model Durations



Space Project Case Study Simulation Results

- The data tables from the Overall RM Model simulation runs over the three case studies were extracted to MS Excel to allow an analysis of the results to calculate how much improvement the optimized option provided for labor costs, COSYSMO calculated systems engineering labor, and direct costs due to change cycles.
- The results of the labor savings in the data tables are converted to dollar saving using the inputs of $100/hr and 160 hr/month.
- The labor hour costs were added to the direct cost savings simulation data to show total cost savings for each project using the optimized processes.

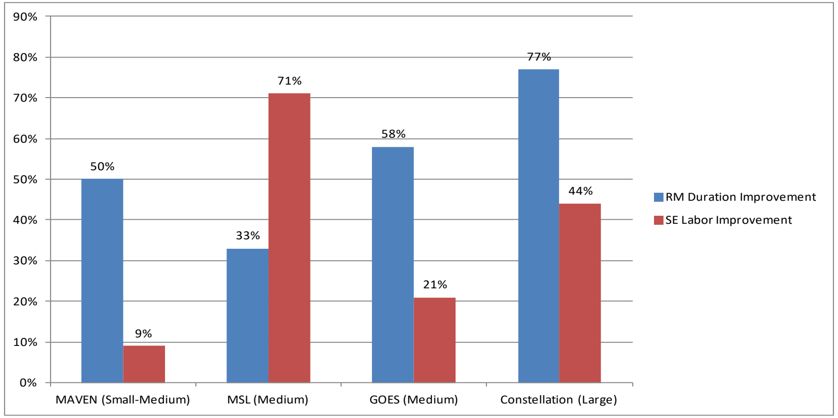
Space Project Case Study Case Inputs

Parameter	Case Study 1	Case Study 2	Case Study 3
TBX Count (% of requirements)	25%	50%	25%
Duration to Make	10 months	10 months	10 months
Product Needed	13 months	13 months	13 months
Delay Costs per Month	$50,000	$50,000	$50,000
Costs per Change	$75,000	$75,000	$150,000
Instability ratio change per month	0.1	0.1	0.1

Space Project Case Study Total Cost Improvements

Name	Case Study 1 Total Improvement	Case Study 2 Total Improvement	Case Study 3 Total Improvement
MAVEN	$ 719,359	$ 894,159	$ 1,040,359
MSL	$ 8,776,889	$ 8,950,931	$ 9,097,889
GOES	$ 2,632,300	$ 2,714,021	$ 2,785,300
Constellation	$ 44,173,129	$ 44,347,356	$ 44,494,129
HLS	$ 17,515,748	$ 17,690,966	$ 17,836,748

Space Project Optimized Requirements Management Process Labor Improvement (Task durations and Project SE Predicted Labor)

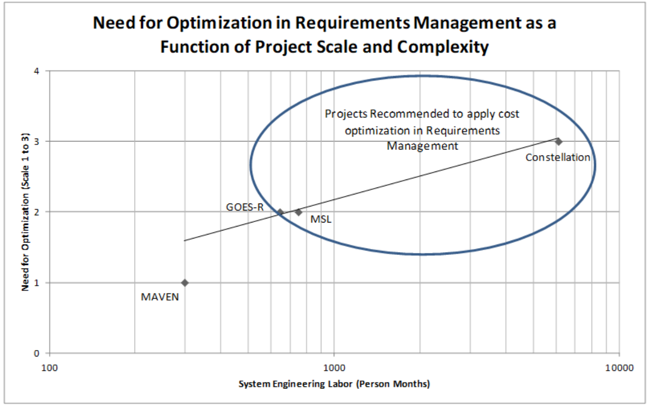


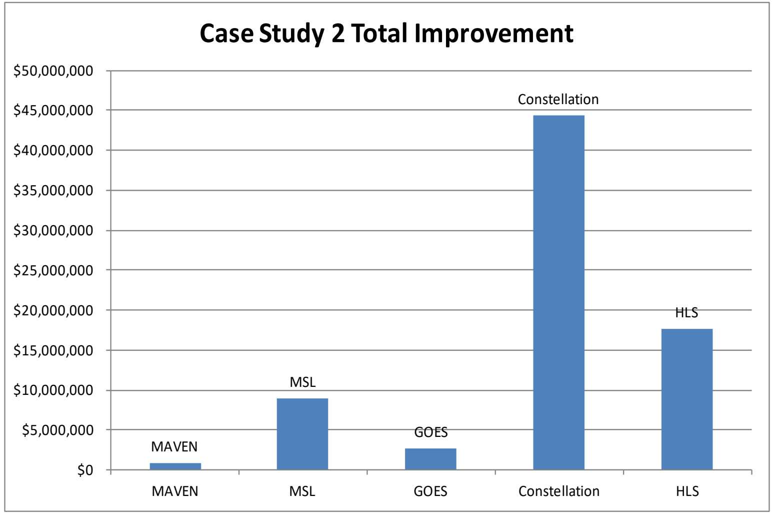
Space Project Case Study Results

- Comparing the benefits found among the different projects, it is observed that the amount of total cost savings of using the optimized approaches per project aligns with the earlier observations on which projects would benefit from an optimized approach.

- A question for any project is whether to invest in the purchase of new tools, process updates and training of personnel, which can be time consuming and expensive (~$50k - $100K).

- Looking at the analysis results, it appears that for complex projects the savings in time and cost could warrant upfront investment to implement the new approaches.





RECOMMENDATIONS

Summary and Recommendations

- Considering the scale of space system development there is potential for companies to price themselves out of a competitive market with unaffordable products; there is a strong need to improve project management processes to yield minimized development cost while still meeting schedule, technical and customer acceptance.

- The requirements management process model provided in this dissertation addresses these parameters and provides options for companies to implement when developing space systems.

- The next slide presents a checklist for an organization to evaluate their options in conducting requirements management, containing recommendations based on the research done within this dissertation.

Requirements Management Approach Recommendations

#	Process Recommendation	Life Cycle Phase	Considerations
1	**Select whether a "document centric" or "data centric" requirements management approach will be applied.** *For complex projects with significant amount of specifications and standards, the selection of a data centric approach is advised to realize cost and schedule savings compared to the investment of establishing this process for a project.*	Project Proposal/ Pre-Award	Project complexity (technical performance and product structure), document quantity, existing processes at the organization, required effort to develop updated processes.
2	**Select a Requirements Management Tool for the project.** *For new development projects with a significant number of requirements, the selection of a user-friendly and collaborative requirements management tool is advised to realize cost savings compared to the cost of a new tool and associated training required.*	Project Proposal/ Pre-Award	Amount of requirements, expectation on maturity and change evolution based on product being developed, existing tools, costs to purchase any new tools, associated training costs and learning curve schedule impacts.

While this table was specifically generated for application in the development of space systems, the recommendations are applicable to the development of any complex system

#	Process Recommendation	Life Cycle Phase	Considerations
3	**Ensure requirement quantity and quality is addressed during the requirements development effort.** *The amount of time spent ensuring the requirement set is minimized and consolidated for the project may vary, but for complex projects with a significant number of requirements it is advised that the time invested early to improve the requirement set (reduce overlaps, minimize the amount of requirements to a set of singular requirements that are necessary) will yield benefits in labor costs and schedule later in the project life cycle.*	Project Start - Preliminary Design Review	Amount of initial set of requirements, project complexity in product structure, amount of outside organizations receiving the requirements; usage of standards such as INCOSE Guide for Writing Requirements provides the methods to achieve requirement quality.
4	**Select the timing to levy requirements on any subcontractors that will be developing products.** *Based on requirements maturity, evaluate whether to 1) wait on establishing the contracts, 2) bring on the subcontractors with a contract to help advance the preliminary requirements while working early development activities, or 3) establish the contract with an official set of requirements.* *For highly unstable requirements, it is advised to either wait to establish the subcontract or to use an approach to have the subcontractor support the requirement development activities; this approach could realize cost savings associated with future change cycles and rework by the supplier.*	Project Start - Preliminary Design Review	Stability of the requirements, heritage of the subcontractor, anticipated cost of future change cycles, anticipated costs associated with any schedule delays of starting development efforts.

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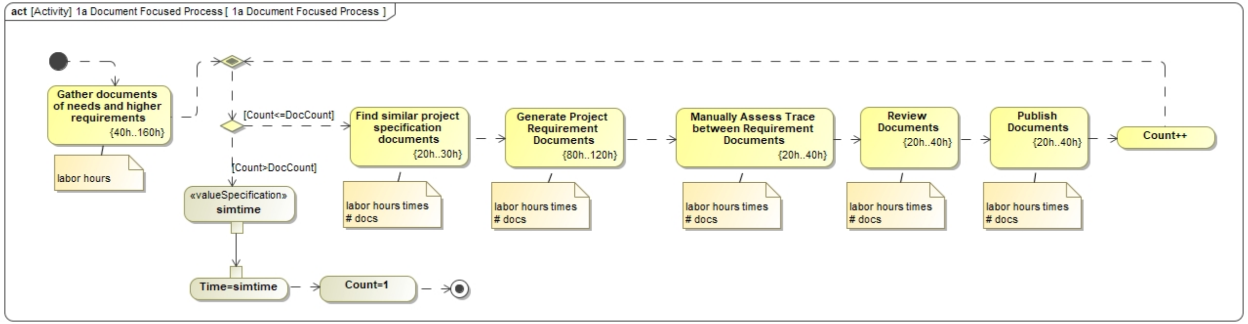
BACKUP

Process 1a and 1b Activity Diagrams

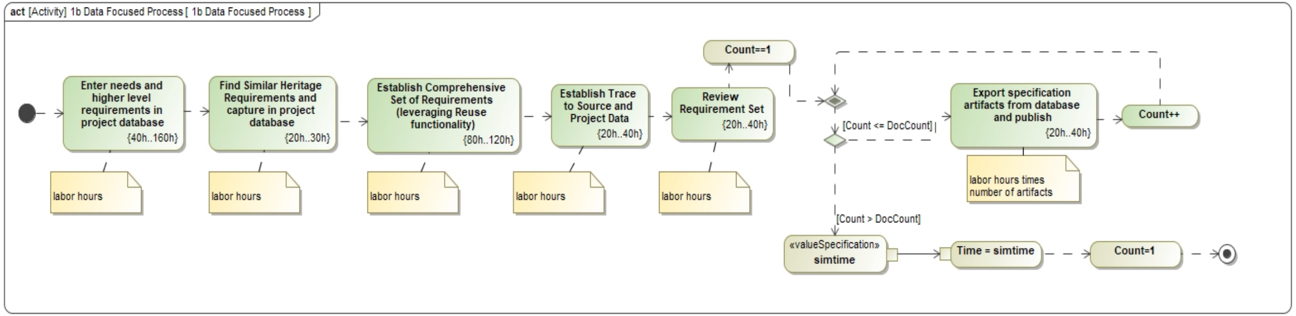
Process 1a, Current State

<u>Document Centric Requirements Management Approach</u>



Process 1b, Proposed Approach

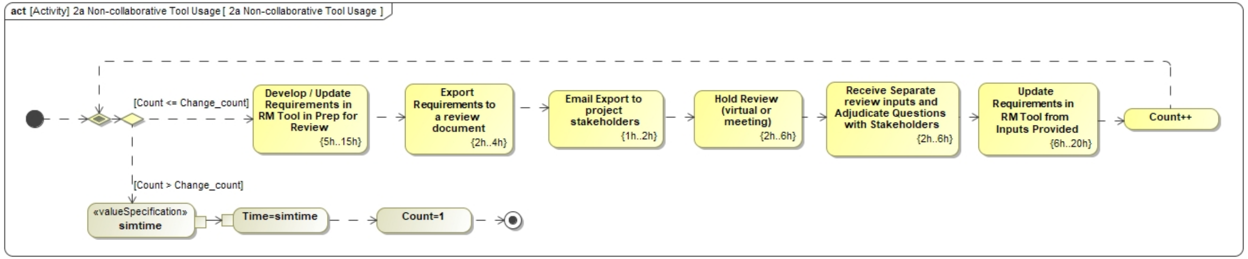
<u>Data Centric Requirements Management Approach</u>



Process 2a and 2b Activity Diagrams

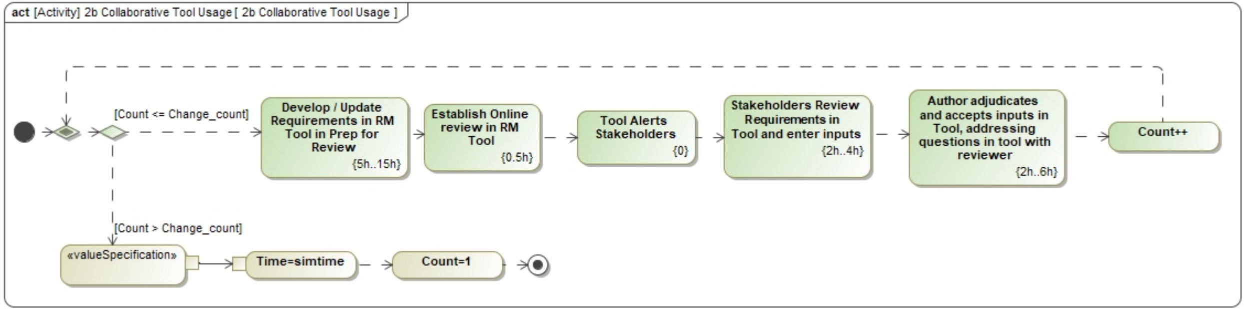
Process 2a, Current State

<u>Usage of a Non-Collaborative Requirements Management Tool</u>



Process 2b, Proposed Approach

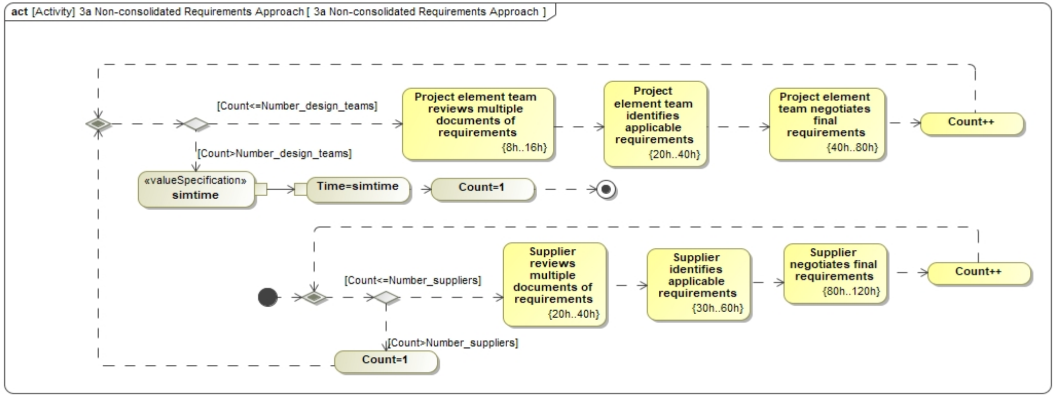
<u>Usage of a Collaborative Requirements Management Tool</u>



Process 3a and 3b Activity Diagrams

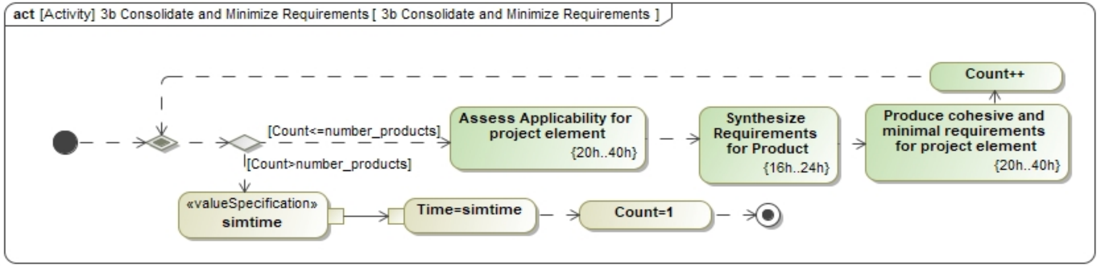
Process 3a, Current State

<u>Non-Consolidated Requirement Set</u>



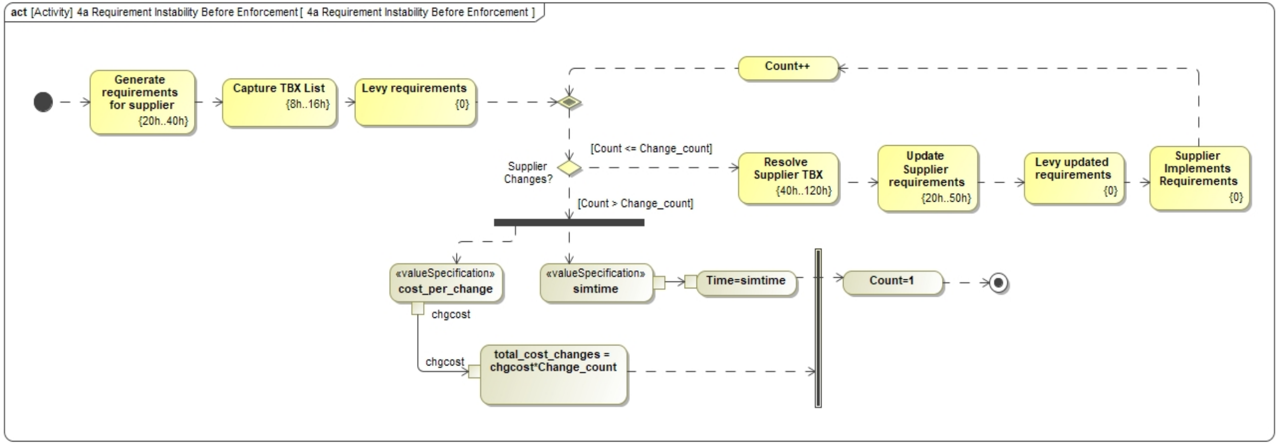
Process 3b, Proposed Approach

<u>Minimized and Consolidated Requirement Set</u>



Process 4a Activity Diagram

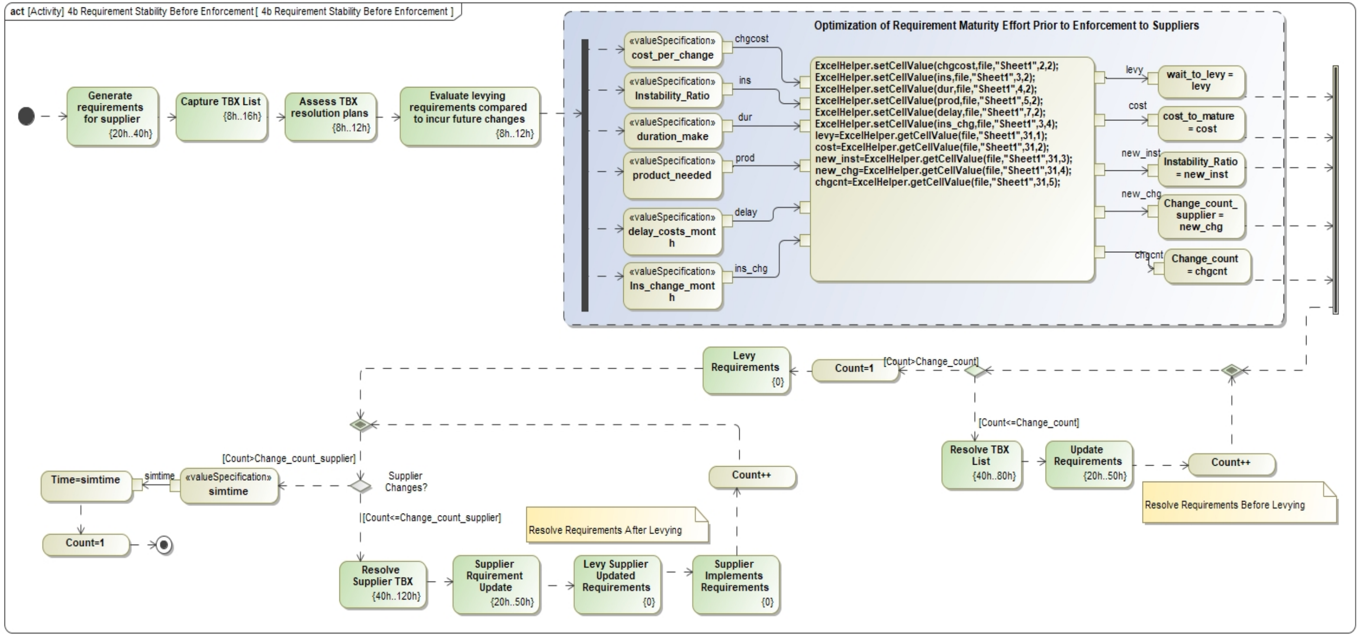
Process 4a, Current State
Levy Unstable Requirements



Process 4b Activity Diagram

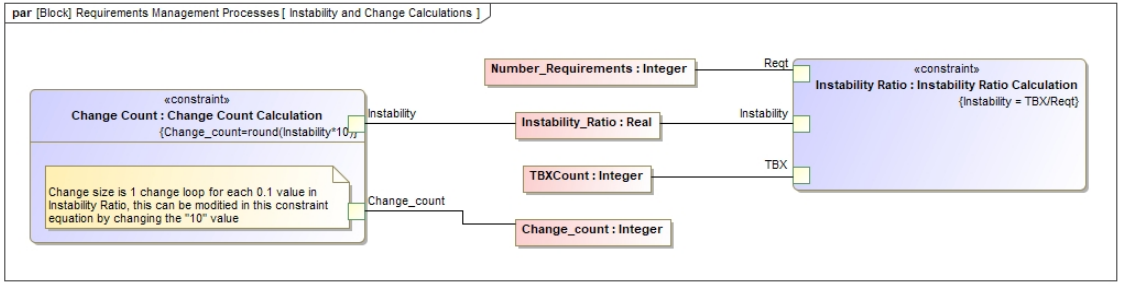
Process 4b, Proposed Approach

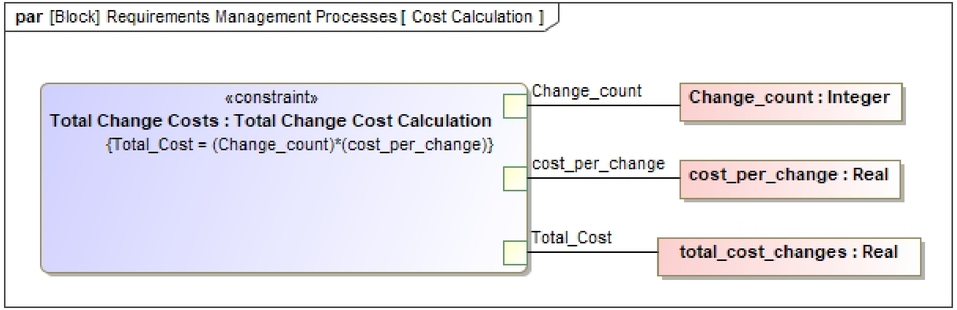
<u>Stabilize Requirements before Levy</u>



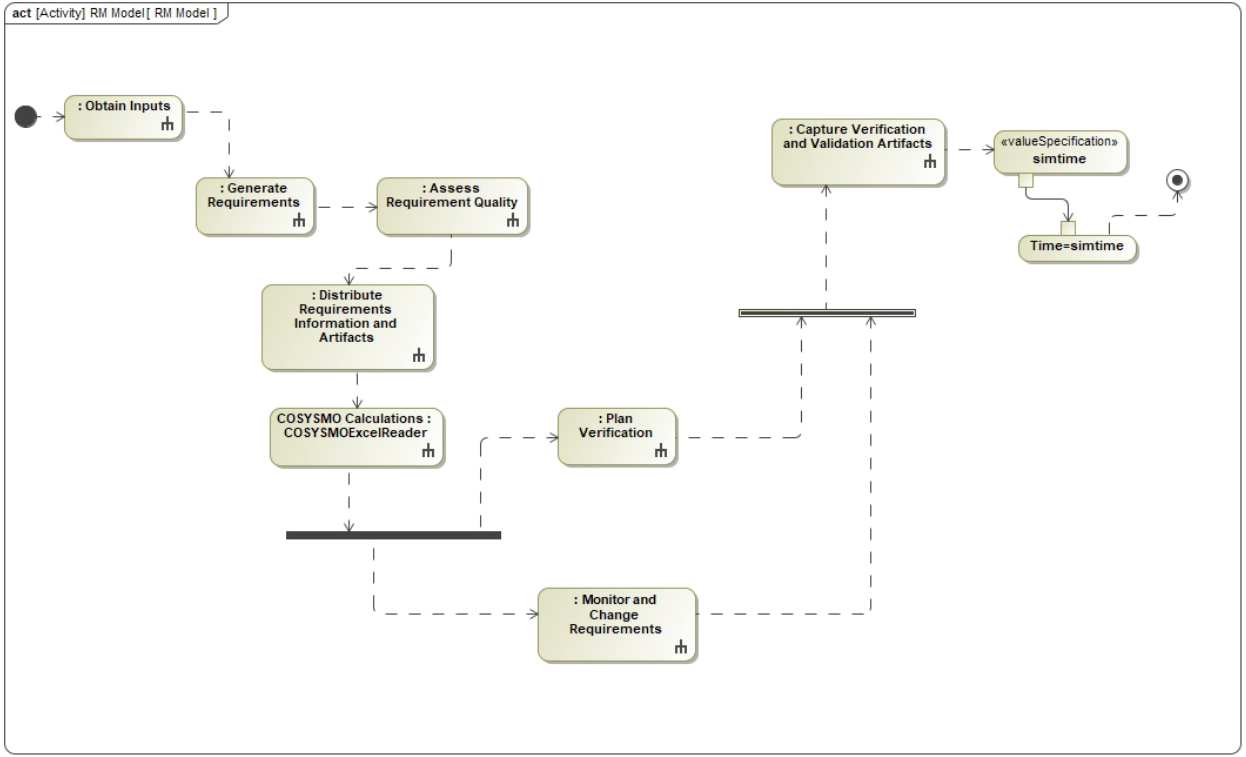
Process 4 Model Additions

- The major change for Process 4 usage of a parametric diagram for value calculations as well as incorporation of an Excel file into the model for the change cost optimization determination.
- The parametric diagrams were used to calculate parameters used in the activity flows; these calculations occurred as soon as the simulation was executed.
- TBX Count and Number of Requirements assigned values resulted in an Instability Ratio value, which was used to calculate the number of change cycles (Change Count), which was then used to calculate the Total Change Costs.





Overall RM Model Diagram



Resource for SysML Simulation

- Key content on creating simulations is found in the Cameo Simulation Toolkit online manual.
- The MBSE Execution YouTube channel was a source of information on how to implement executable SysML using Cameo Simulation Toolkit.
- Specifically, the video on how to use Excel Lookup Table in SysML simulation prompted the effort to integrate COSYSMO and change cost optimization excel files with the requirements management activity diagram. https://www.youtube.com/watch?v=kcu3ofPSjqY
- Other simulation resources include the simulation sample models that come with Cameo Systems Modeler, which demonstrate various simulation techniques.