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Evaluation of Requirements Management Processes Utilizing System Modeling Language (SysML) Executable Models

Contents

- Process investigations and methods for measuring process updates
- Process model evaluation using SysML simulations
  - Overview of Modeling Approach
  - Example of a specific Process Comparison
  - Example of a total set of Process Comparisons
- Conclusions on Approach

Investigating the Requirements Management Process

- Poor requirements efforts have been shown to drive costs and impact technical performance for many past projects.
- Research was done to determine a more cost effective approach towards Requirements Management.
- The goal of the research was to **develop an approach to implement requirements management for a project** that could be tailored towards the project's parameters to enable a cost optimized successful outcome.

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

Historical Costs of Poor Requirements Engineering

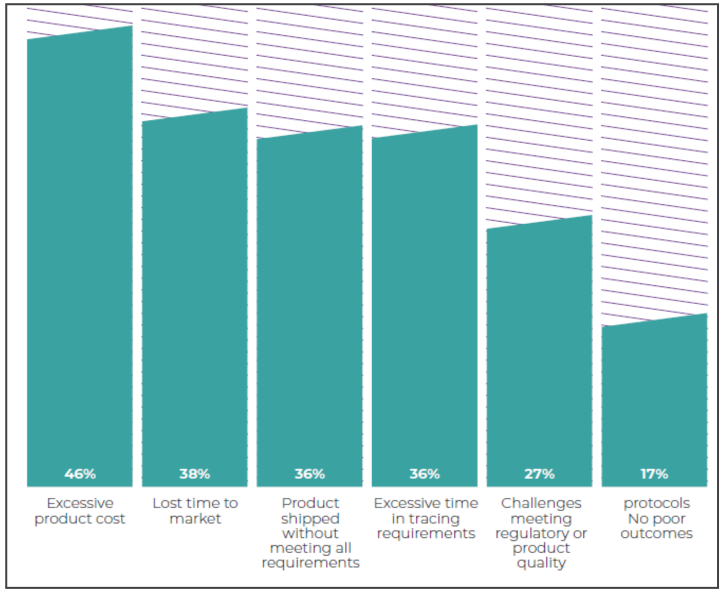
Sample Data on Past Project Impacts:

- NASA studies show 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)

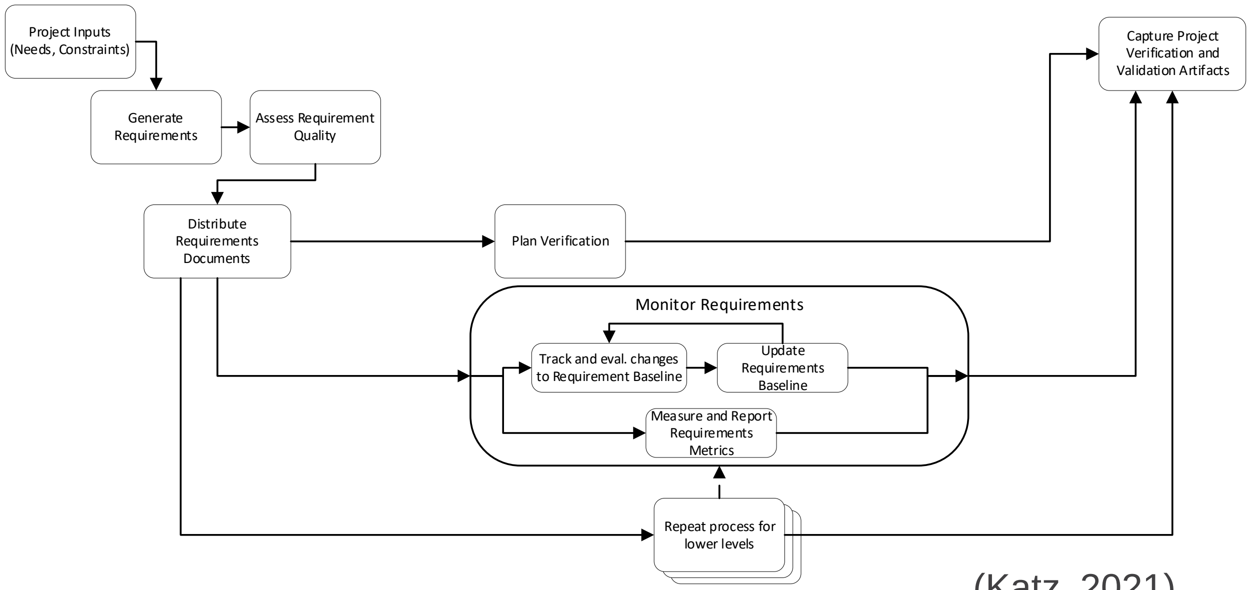


Types of Failures due to Poor Requirements Management. (Engineering.com, 2018)

Generation of a Requirements Management Process Model

- Based on research a process model was developed for the **Requirements Management (RM) Process**.
  - This model provides a high level look at the overall RM process, 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 over a project's lifecycle.

- Note: there are several models that define the *requirements development* process and it was not a focus of this particular study.

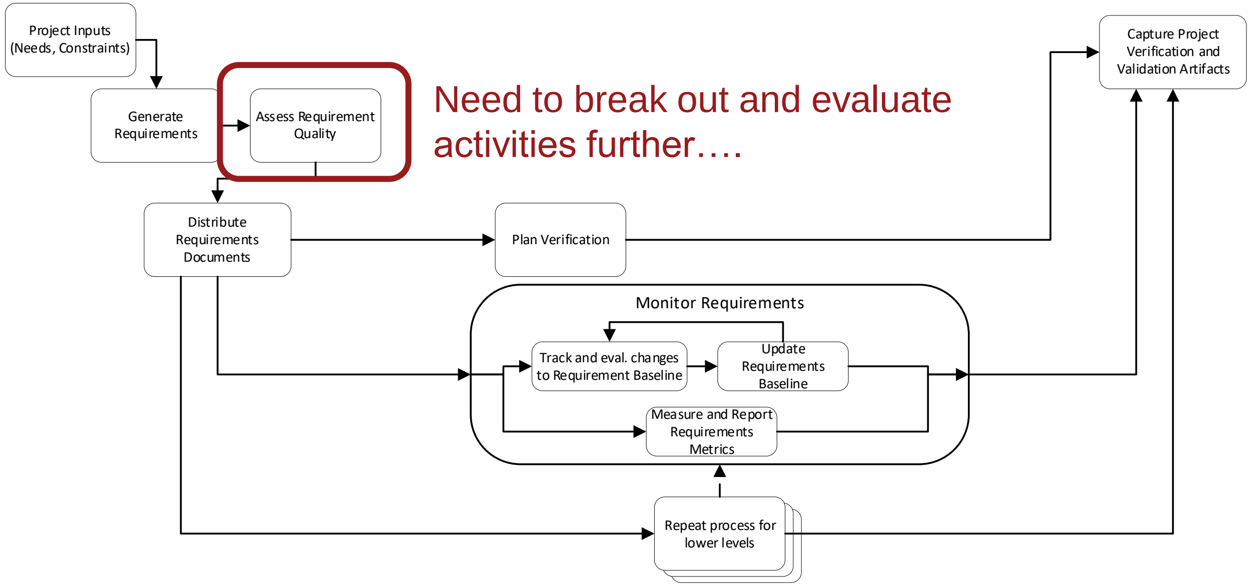


(Katz, 2021)

An RM process model was captured in MS Visio using a "document centric" approach

Process Modeling Options

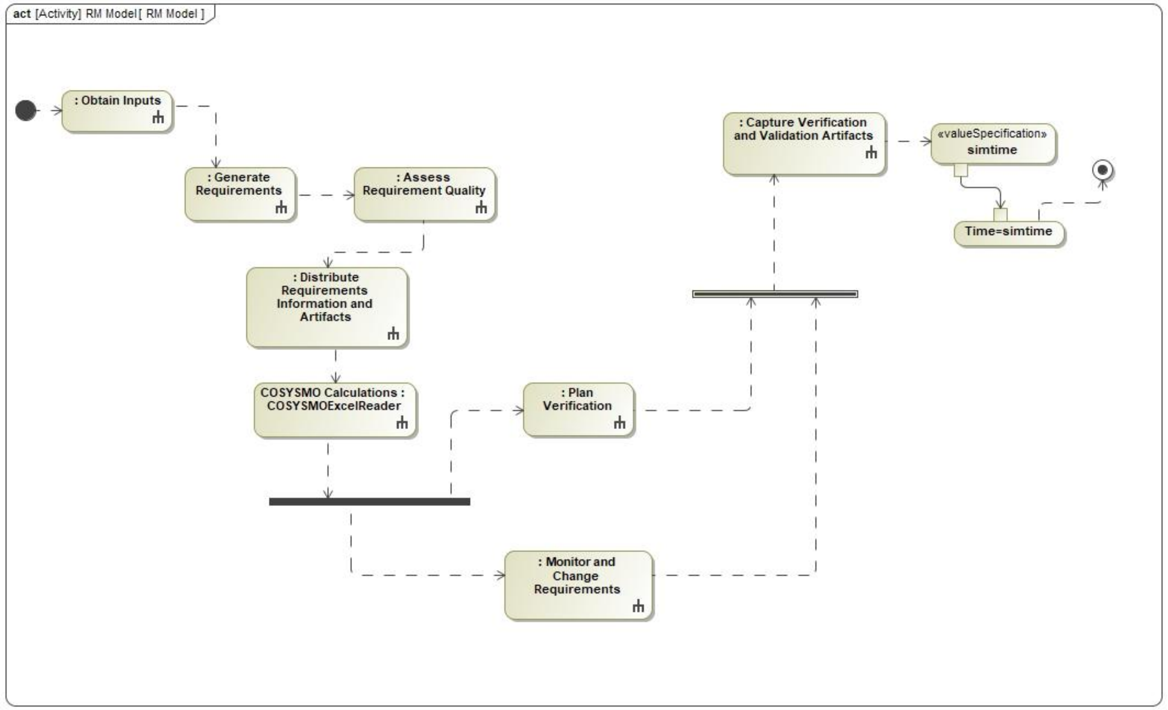
- This RM process model can be used to evaluate various changes and inputs enabling an assessment of the impact to the overall effort.
- Implementing this study via "document centric" approaches can be manually intensive and prone to error!
- Inspired by multiple examples of model based systems engineering (MBSE) demonstrating how activities can be shown in a system model and analyzed for behaviors, the RM Model was ultimately evaluated using SysML simulations.



Needed a way to evaluate each of the activities within the process that enables understanding of impacts to the overall effort.

Generation of a Requirements Management System Model

- The RM process model was modeled as an activity diagram in SysML.
- Activities were modeled at lower levels, enabling a comprehensive model with many layers of activities and options.
- The next set of slides highlights examples of these models, and then shows how they were used in Activity Diagram Simulations to evaluate various parameters of interest.

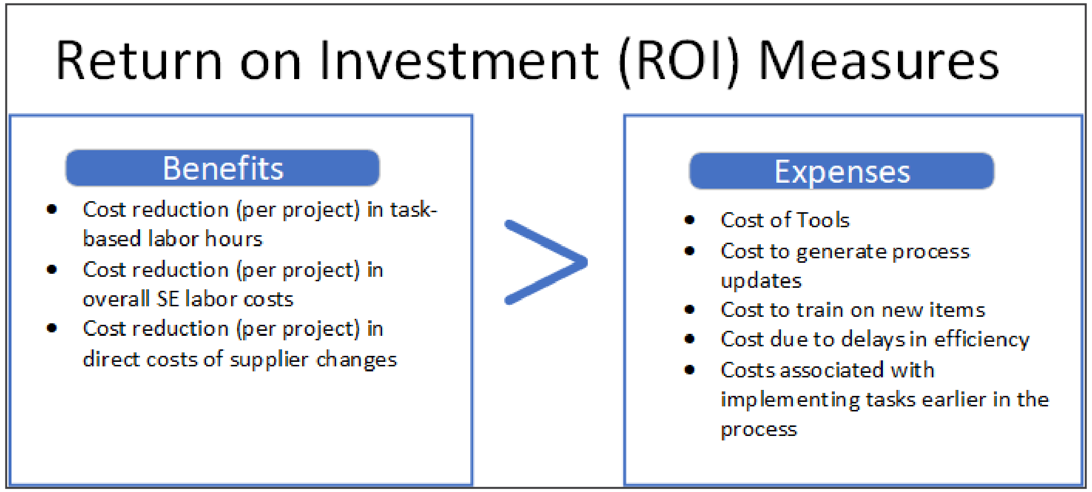


The following slides highlight the details of the model, the simulation effort, and the resultant data. A more in depth presentation is available on the INCOSE RWG YouTube Channel: https://youtu.be/kkyGzHWB1vU

Measures Used to Evaluate Updated Processes

- When considering the application of new 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)

- These parameters can be used in the process evaluations as inputs / constraints and calculated outputs to compare various process options.



Return on Investment (ROI) Measures Utilized

- **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.

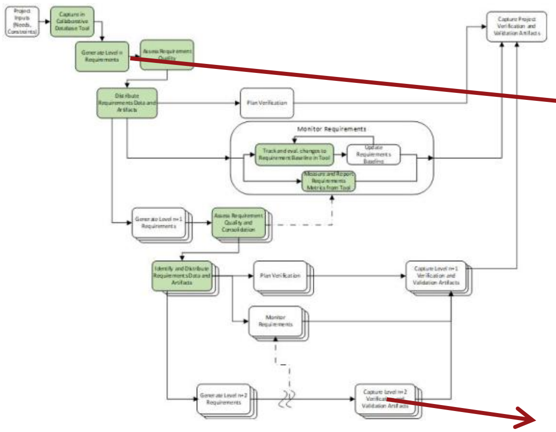
- **Project SE labor hours:** The cost model tool COSYSMO, which predicts systems engineering labor in labor months as a function of requirement quantity and quality, provides a measure of overall project systems engineering labor cost.

- **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.

Task Labor Hour Measures

- Estimated labor hours are 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



Gather documents of needs and higher requirements → Find similar project specification documents → Generate Project Requirement Documents → Manually Assess Trace between Requirement Documents → Review Requirement Documents → Publish Requirement Documents

Gather documents of needs and higher requirements	Find similar project specification documents	Generate Project Requirement Documents	Manually Assess Trace between Requirement Documents	Review Requirement Documents	Publish Requirement Documents
Labor hours	Labor hours times number of documents	Labor hours times number of documents	Labor hours times number of documents	Labor hours times number of documents	Labor hours times number of documents

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 Cost Measures

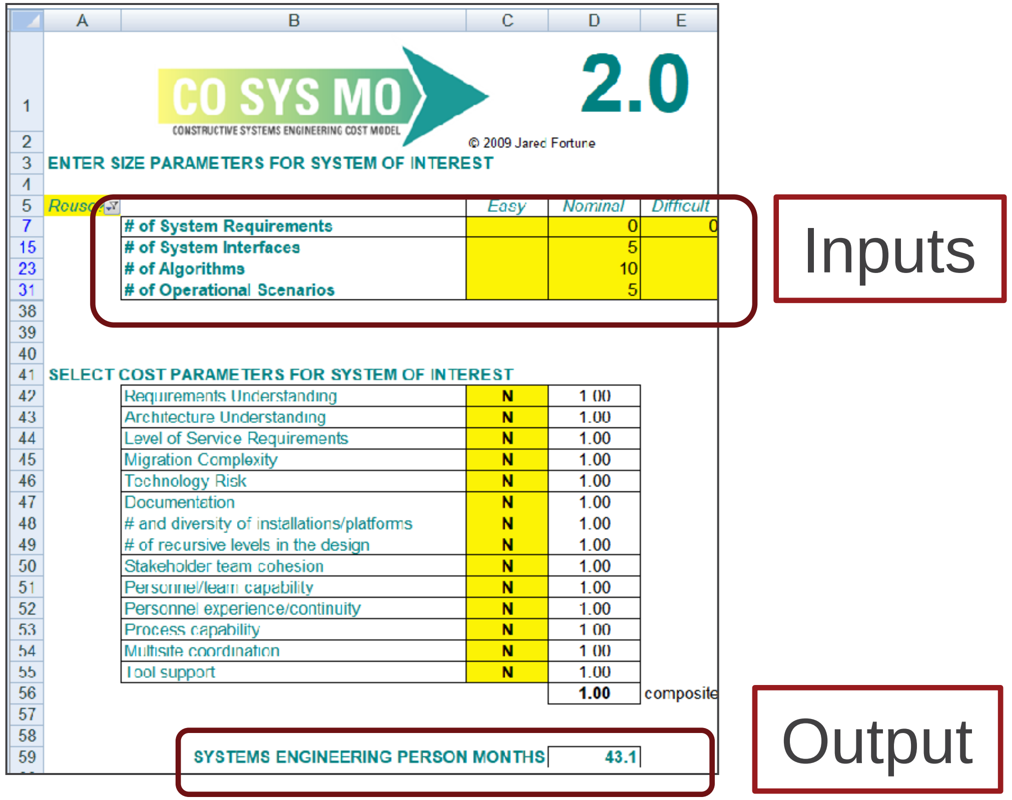
- The Constructive Systems Engineering Cost Model (COSYSMO) is a parametric model for estimating the systems engineering effort required for the development of space systems.
- COSYSMO can provide a predicted systems engineering labor in months based on inputs, which include requirement quantity and 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

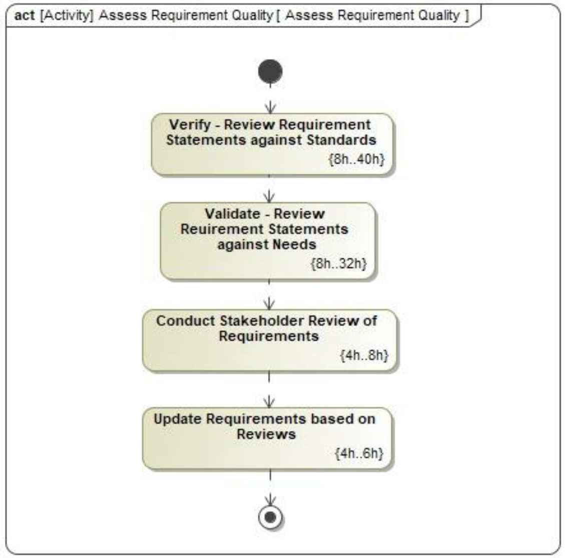


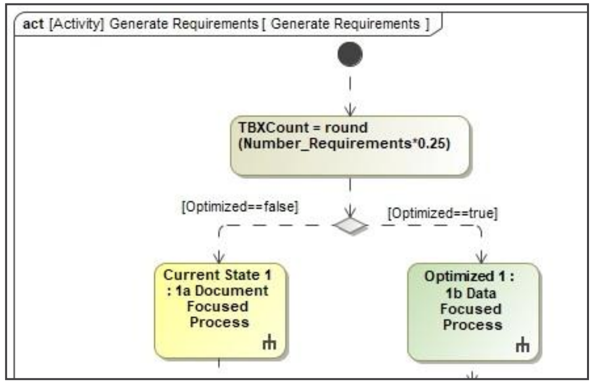
COSYSMO Cost Model. (Valerdi, 2010)

Modeling Techniques Used

Process Activity Diagrams

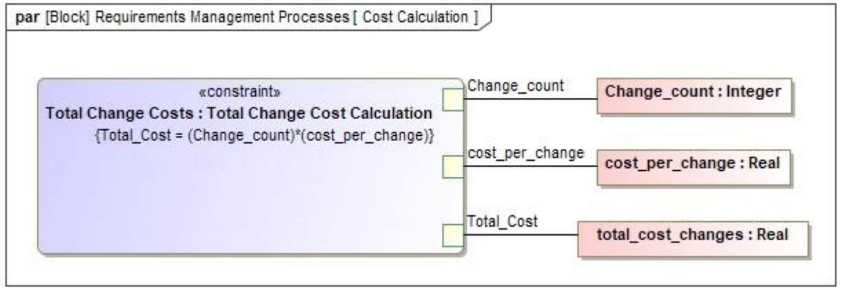
- Lower level activity diagrams are created to reflect specific task actions.
- Duration constraints are applied in these actions to calculate total time for the activity (using a minimum and maximum set of times).
- Decisions are put in place to establish which set of activities are evaluated (optimized or current state).
- Process "instances" are created to set the initial parameter values for the process activity (such as usage of optimized path, or number of requirements on the project).

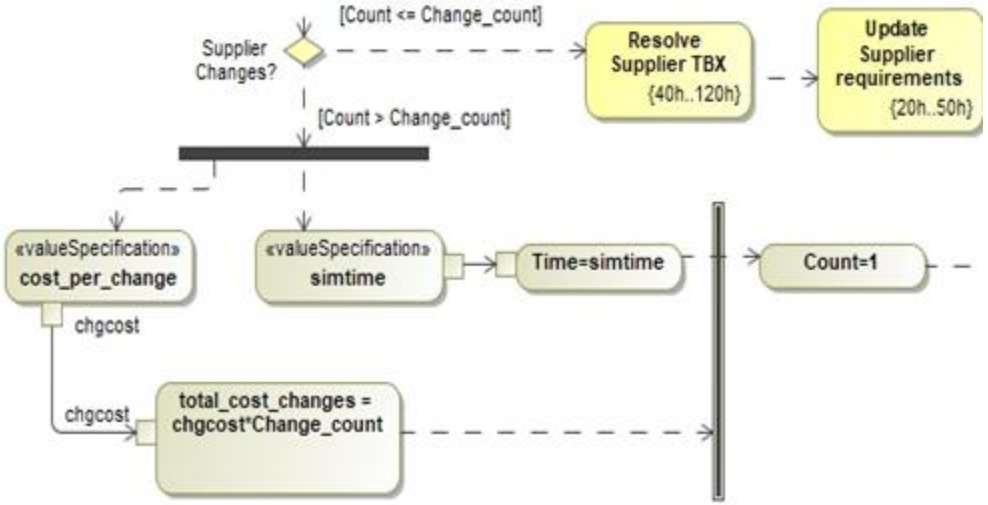




Data Calculation

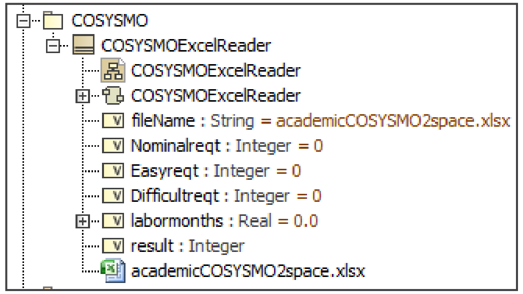
- Multiple methods of calculating data based on process parameters were used in this model.
  - Parametric Diagrams enabled calculation of parameters based upon project inputs.
  - Opaque Actions enabled calculation of parameters based upon location within an activity diagram.
  - Simulations enabled calculation of time parameters based upon activities and loops (counters).
  - Excel files imbedded in the model (next slide)

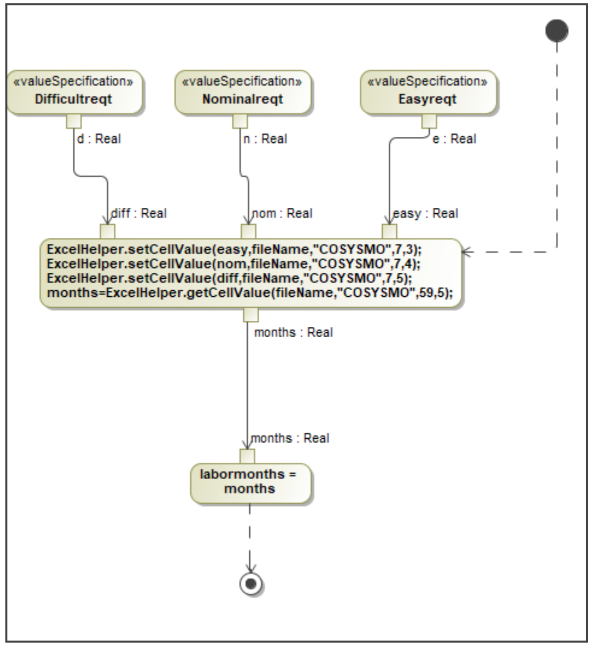




Using Excel in the SysML Model

- Excel files are able to be integrated into the SysML model and used to perform operations within the model.
  - Useful Tutorial: https://www.youtube.com/watch?v=jk32emTYN4Y
- An opaque action is used in the activity diagram to supply input parameters to the excel file and extract resultant parameters during the simulation.
- Similar interfaces can be done with MATLAB functions, however it was not utilized in this project as Excel was adequate for the calculations in this particular research effort.

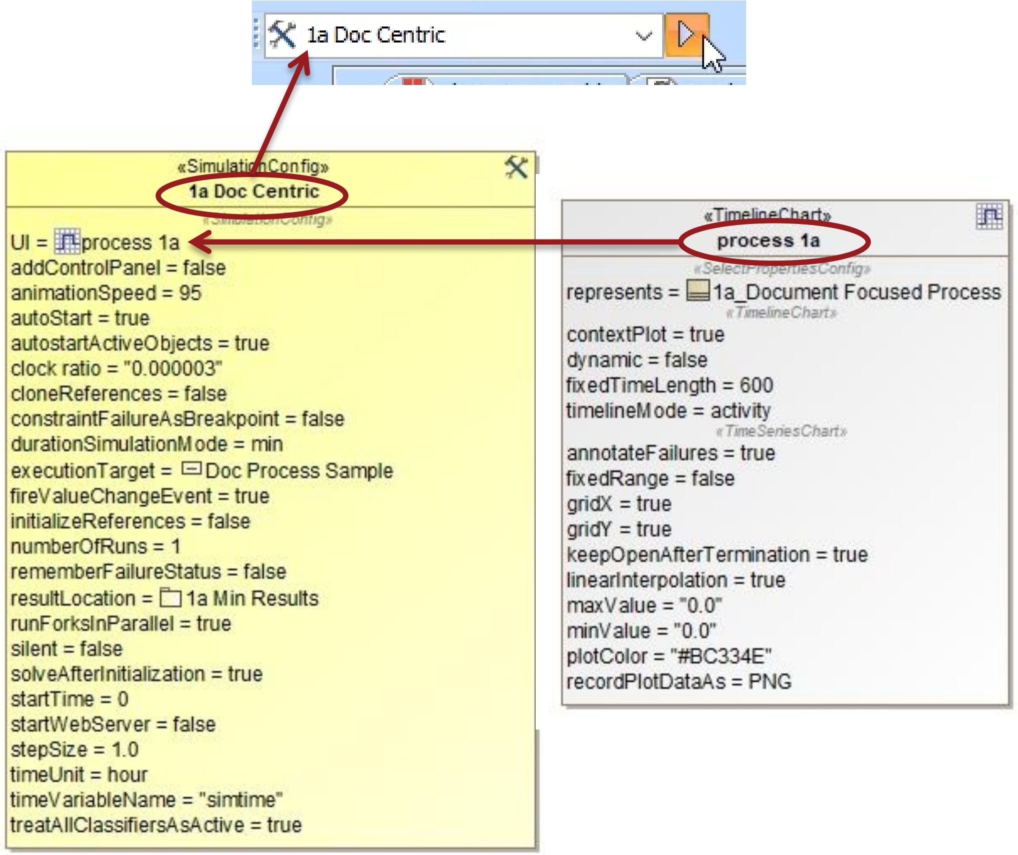




Process Simulations

- Activity diagram simulations are established using a *Simulation Configuration* block.
  - The Name in the block correlates to the Simulation
  - The *execution target* is set to the process instance, which calls the activity diagram for that process.
  - The *clock ratio* establishes speed of simulation, with ability to run faster than real time.
  - The *resultLocation* establishes location of the folder that captures the resultant instances created during the simulation, providing the output parameters from the simulation (such as total time).
  - Simulation *startTime* is set to 0 (allowing the 'timer' to start at the beginning of the simulation), and *timeUnit* establishes how the time is measured (example here is set to "hour").
  - The simulation *timeVariableName* sets the name of the parameter that holds the calculated simulation time (example here is set to "simtime").
  - The *durationSimulationMode* sets whether the minimum or maximum duration constraint values are used, or their average.

- A *Timeline Chart* enables a graphical representation to show the durations of various actions as the simulation is executed. It is invoked by the Simulation Configuration in the *UI* field.



Example Process Evaluation

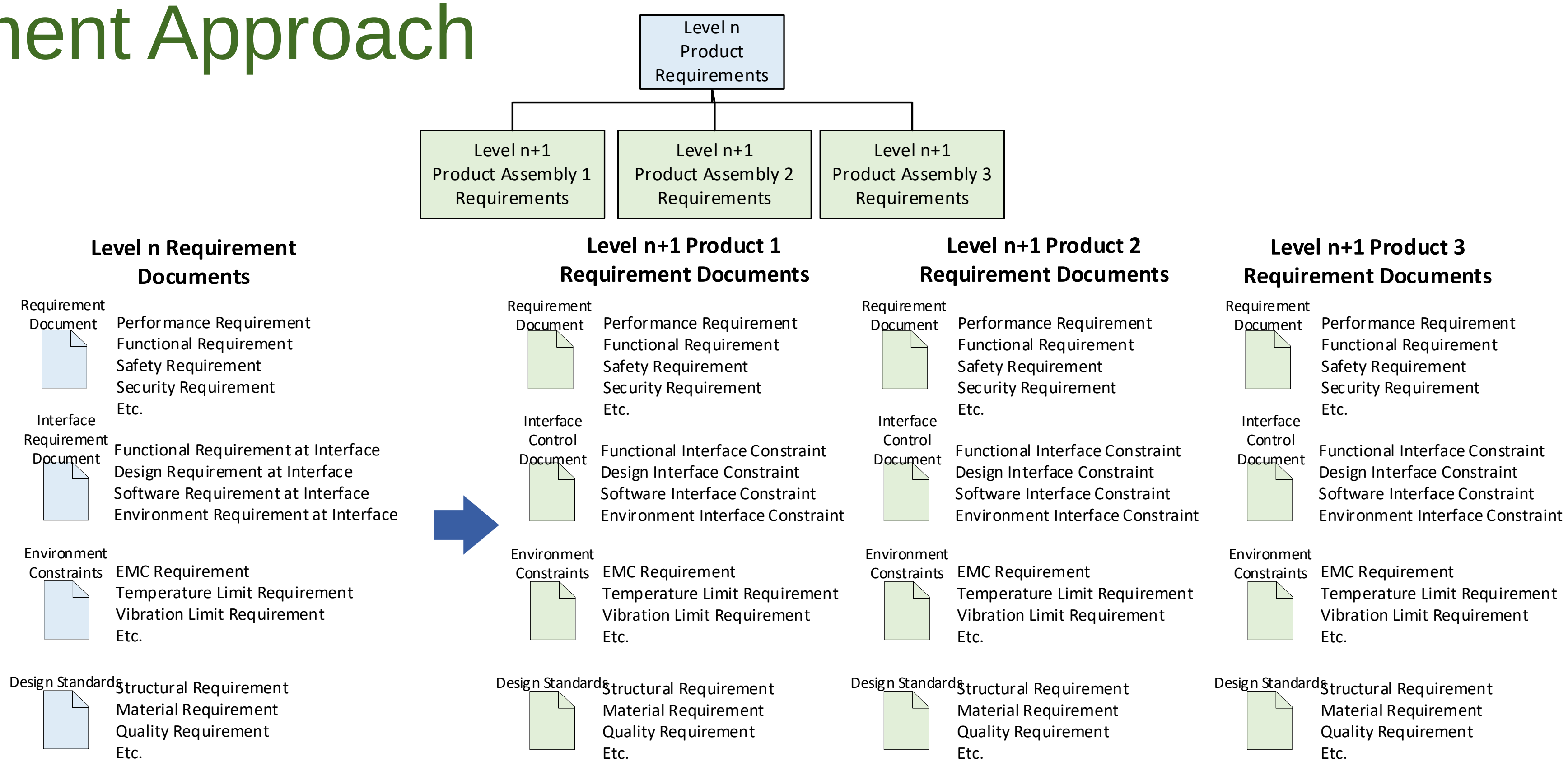
Process Evaluation Example

- The next set of slides provides a demonstration of using the SysML process model in evaluation of two process options.
  - Process 1a – A “document centric” requirements management approach
  - Process 1b – A “data centric” requirements management approach

- Each process was captured as a set of activity diagrams that were then simulated to calculate total labor hours for the effort as a function of number of requirement documents.

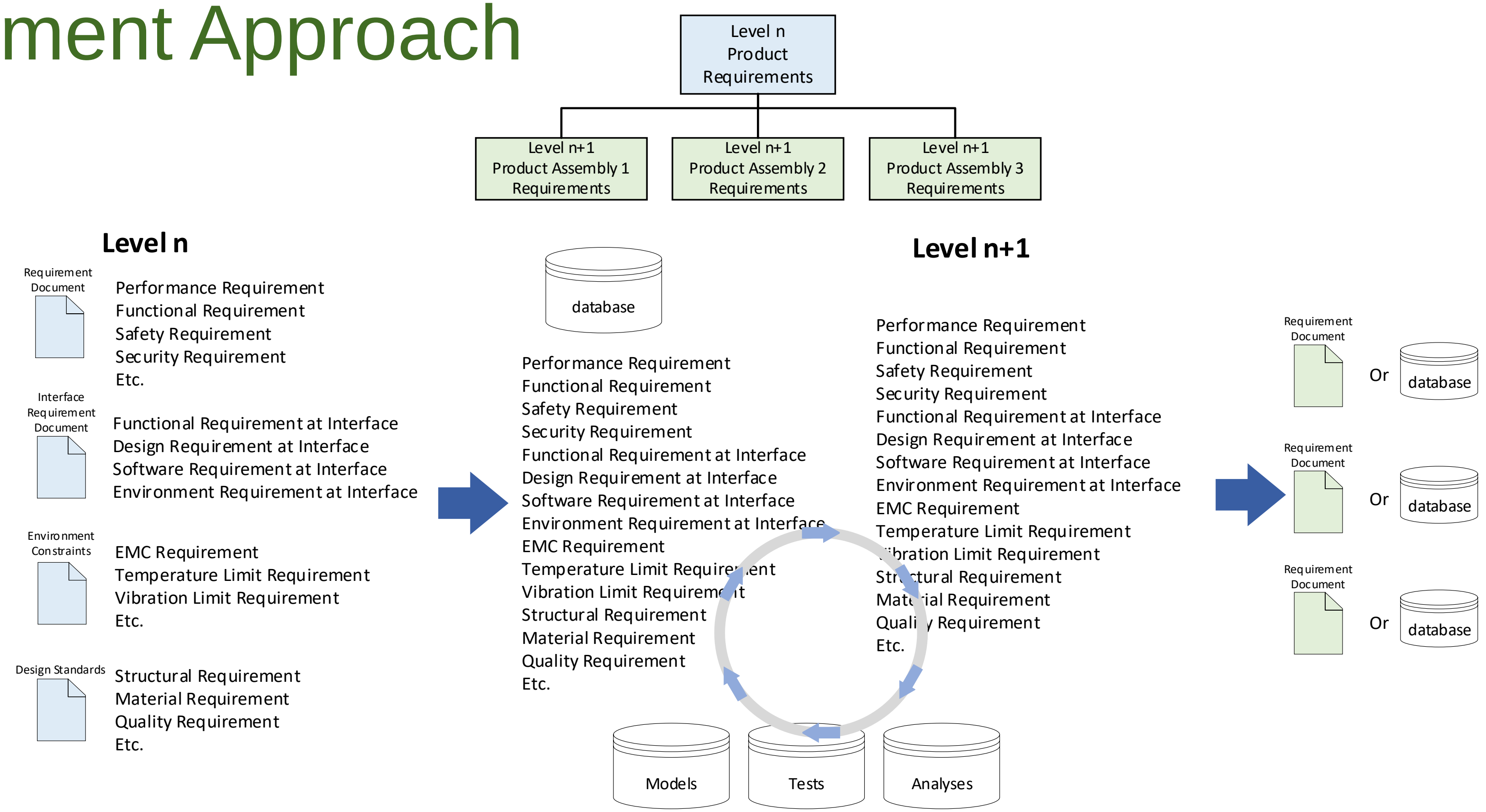
- Results were captured in a SysML instance table, and then exported to Excel for further data analysis.

Process 1a - Usage of a Document Centric Requirements Management Approach



The “document centric” approach uses individual requirement specifications for all types and levels of requirements.

Process 1b - Usage of a Data Centric Requirements Management Approach



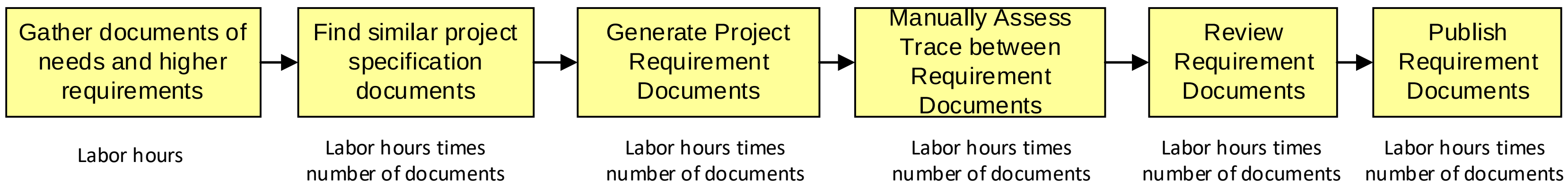
The "data centric" approach treats all requirements as a set of project data, compared to compartmentalized specification documents, enabling reduction in overlaps, closure of gaps, reuse of requirements at multiple levels, and trace to other project data.

Process 1a and 1b Activities and Measures

- 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.

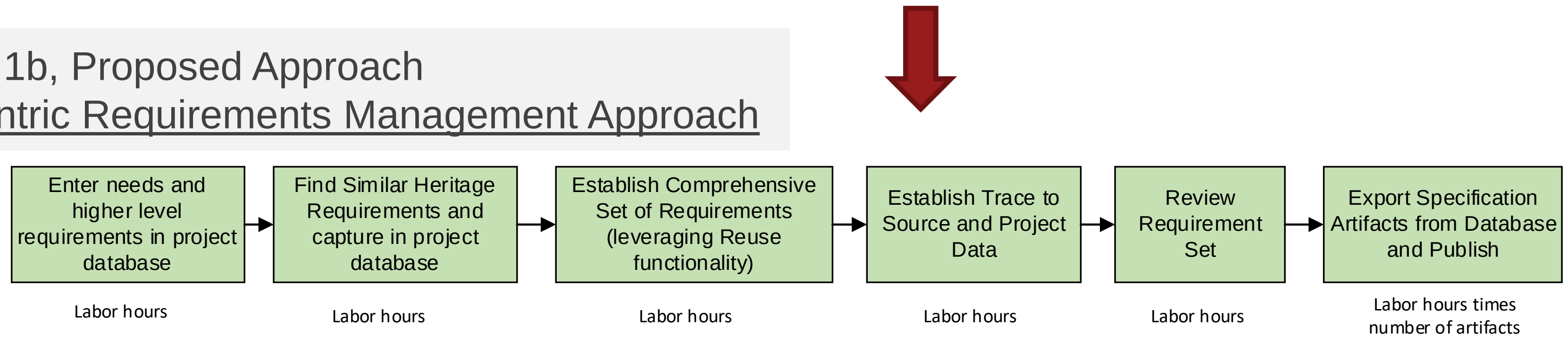
Process 1a, Current State

Document Centric Requirements Management Approach



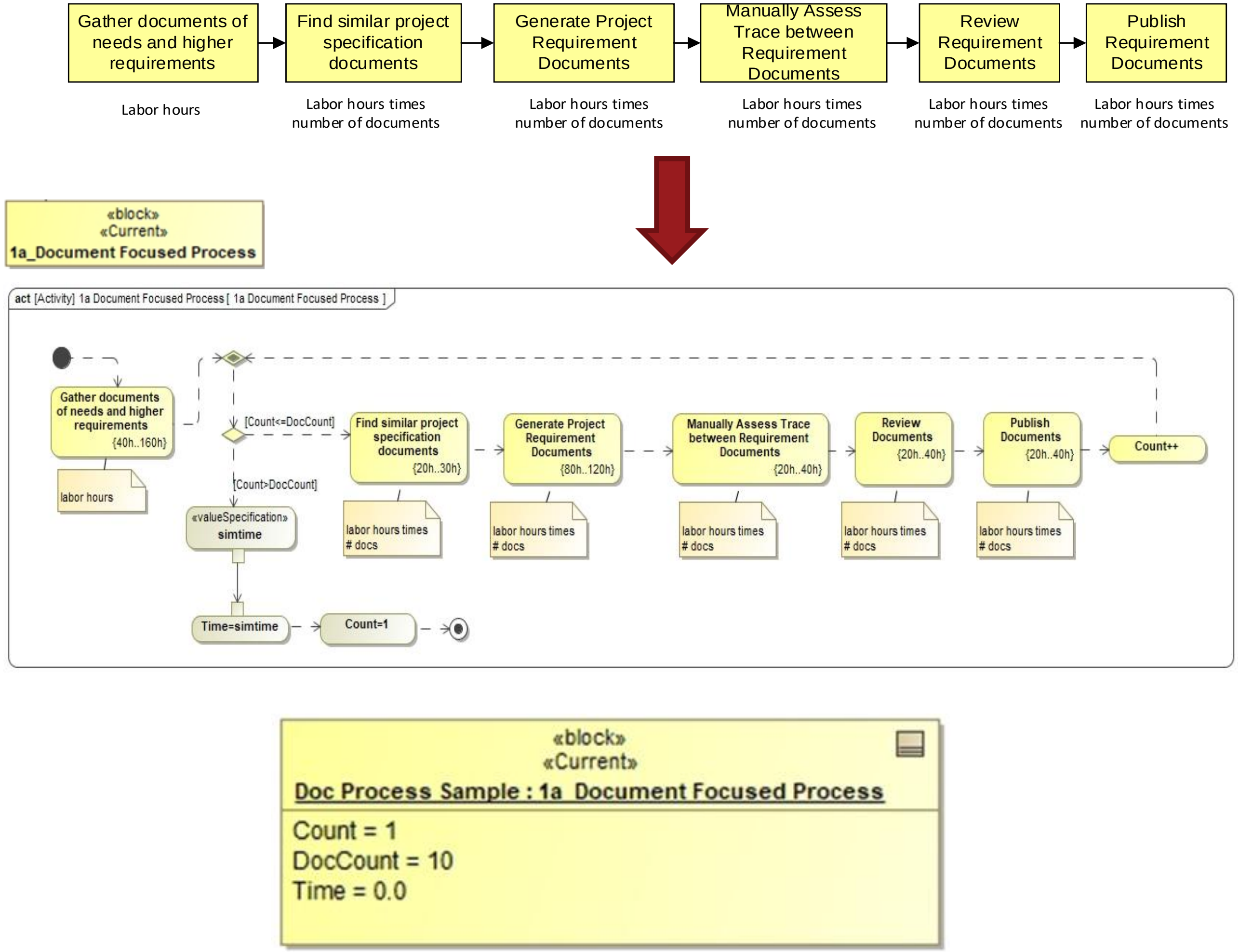
Process 1b, Proposed Approach

Data Centric Requirements Management Approach



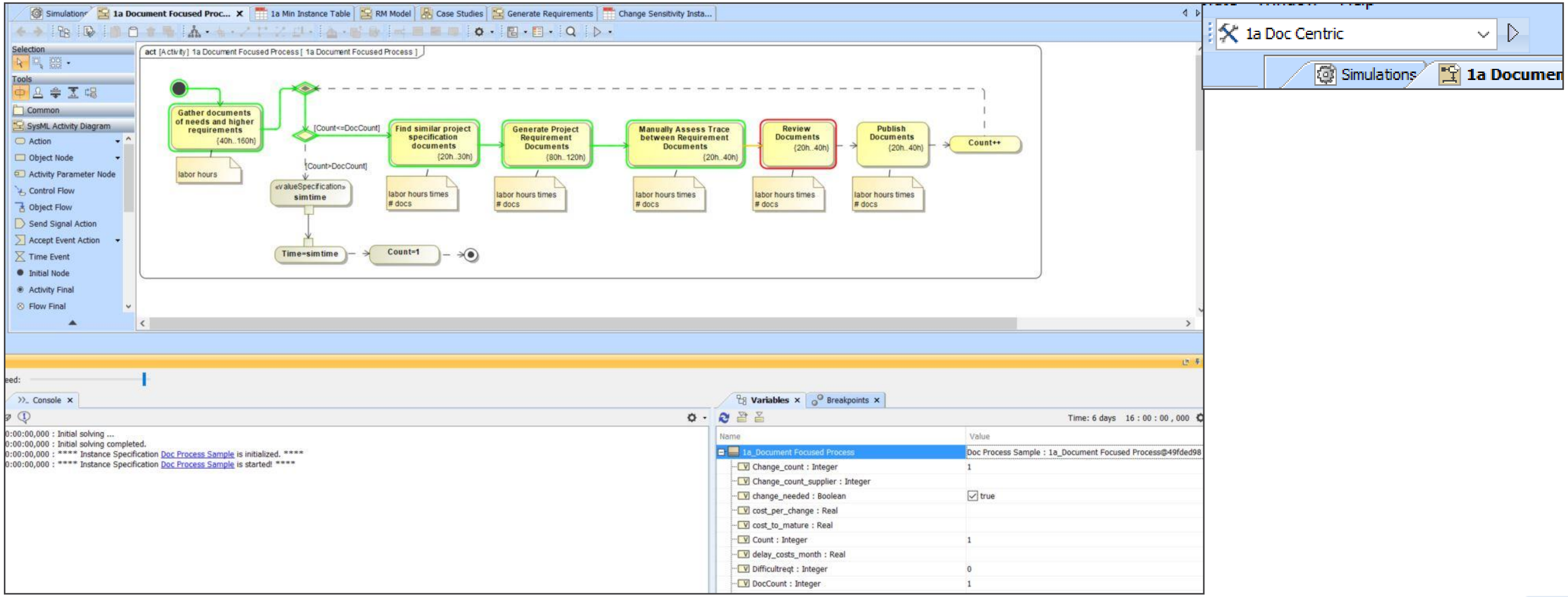
Process 1a SysML Model Overview

- 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.



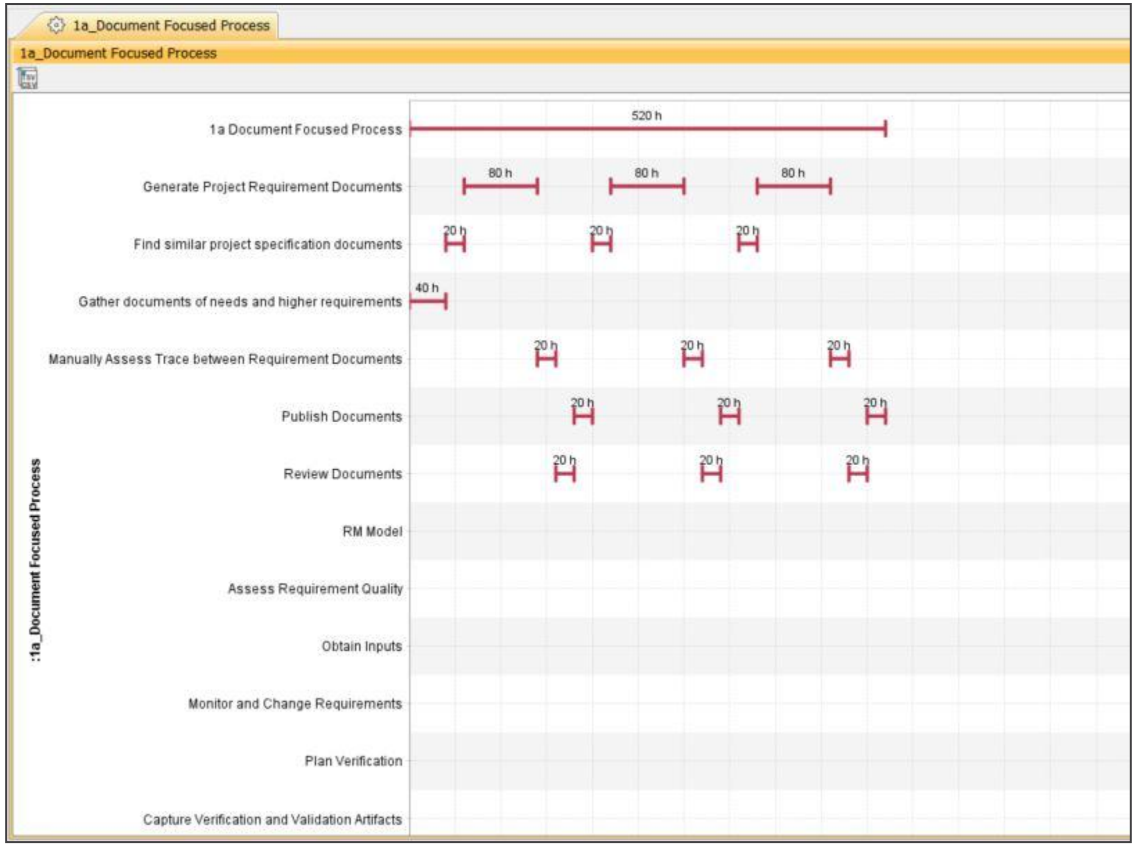
Process 1a Simulation Run

- 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.



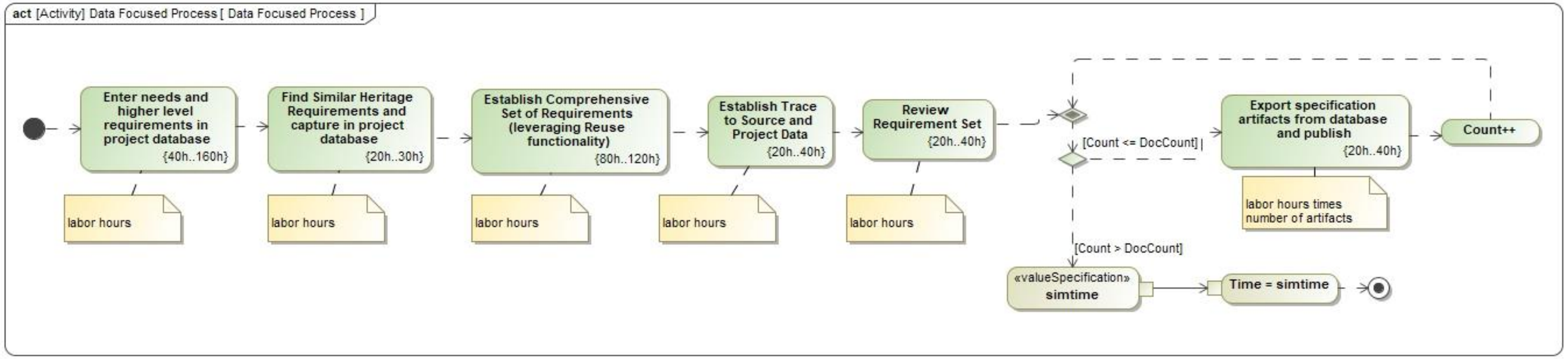
Process 1a Simulation Run (cont.)

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



Process 1b SysML Model Overview

- Like Process 1a, the activity diagram for Process 1b uses task labor hours.
- While this process is also a function of document numbers, the documents referenced are extracted from the project database for publishing and delivery (which occurs at the end of the requirement effort).

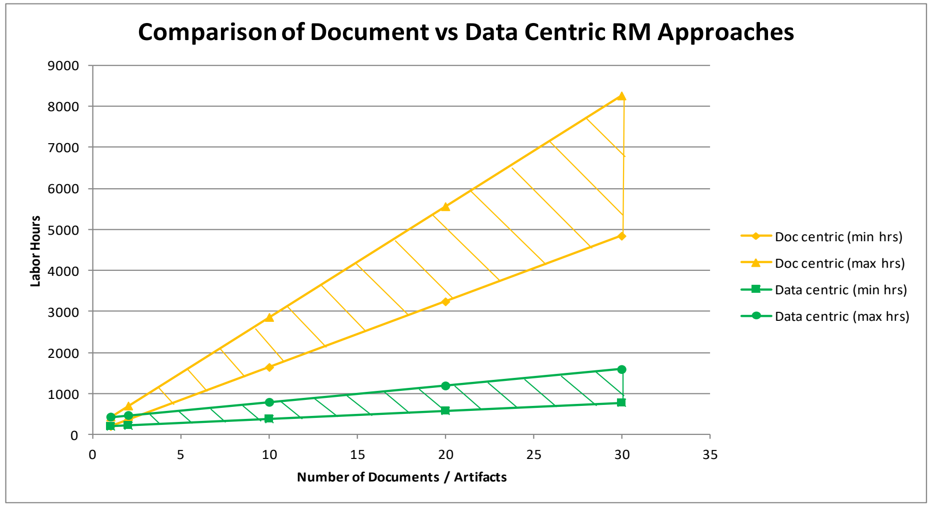


Process 1a and 1b Simulation Results

- 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).
- 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.
- The results of this trade provides the project with data regarding whether the project should invest in pursuing a particular process method:
  - As the project considers the cost of implementing a software application required for using a data centric approach, there is a clear benefit to implementing the data centric requirements management approach for a product containing a high number of requirement documents.
  - There may be less benefit of implementing the date centric for projects that have very few requirement documents (small products with fewer requirements, as example).

#	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

#	Name	DocCount : Integer	Time : time
1	Data Process Sample	1	0
2	1b_Data Focused Process at 2021.01.17 13.57	1	200
3	1b_Data Focused Process at 2021.01.17 13.56	2	220
4	1b_Data Focused Process at 2021.01.17 13.51	10	380
5	1b_Data Focused Process at 2021.01.17 13.52	20	580
6	1b_Data Focused Process at 2021.01.17 13.56	30	780

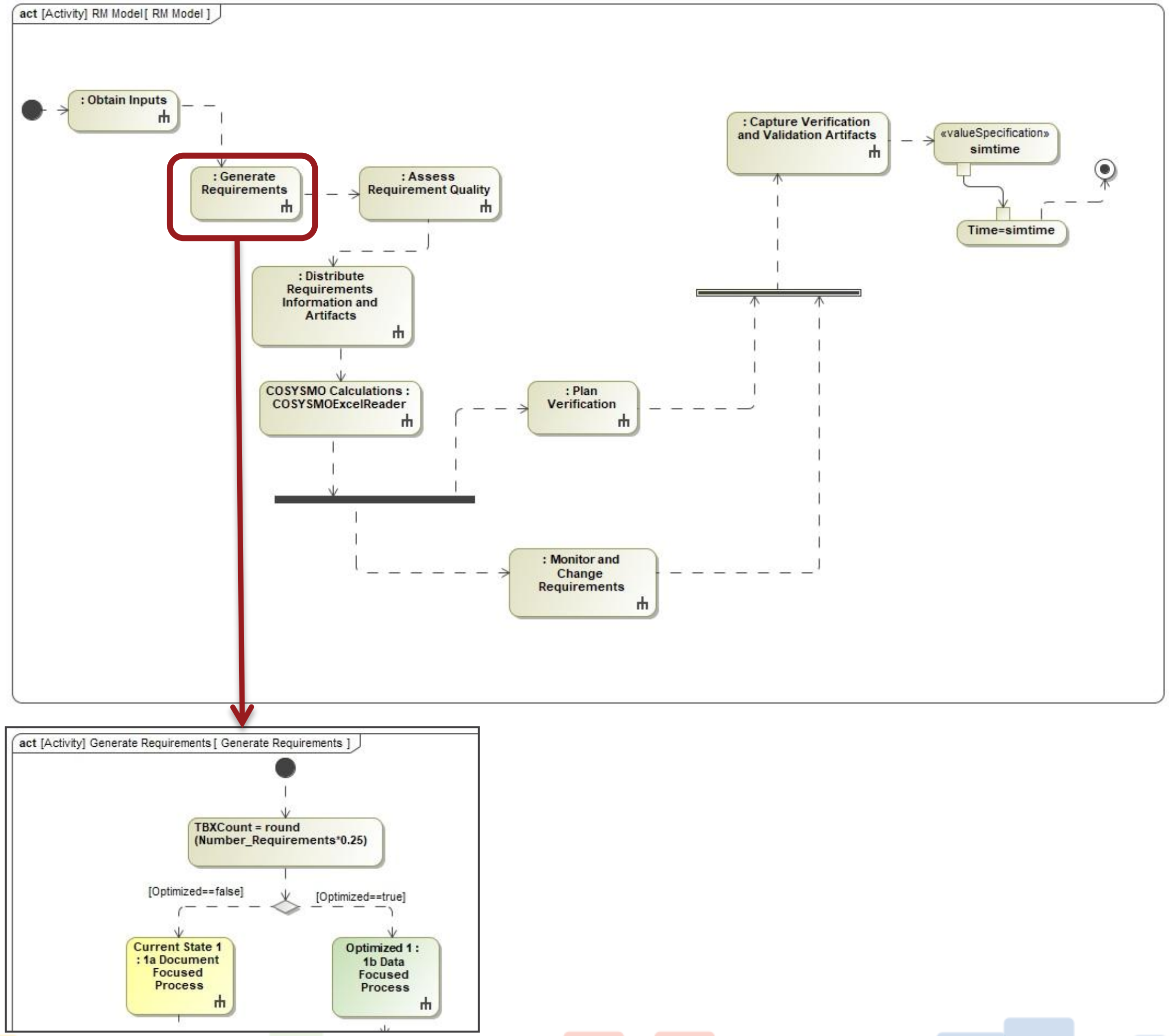


Range of Labor Hours for Current State and Optimized Process based on Total Document Count

Example RM Model Simulation

Simulating the Overall RM Model

- The RM model uses the COSYSMO Excel file to calculate systems engineering labor hours based upon input parameters of requirement quantity and quality.
- The output of this model provides data on task labor hours associated with the requirements management processes, SE Labor time to the project, and direct costs for change cycles.
- The overall model can be simulated to compare a series of process changes and determine the impact for the project for the entire set of updates; Examples of this using past NASA missions is provided in the following slides.



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

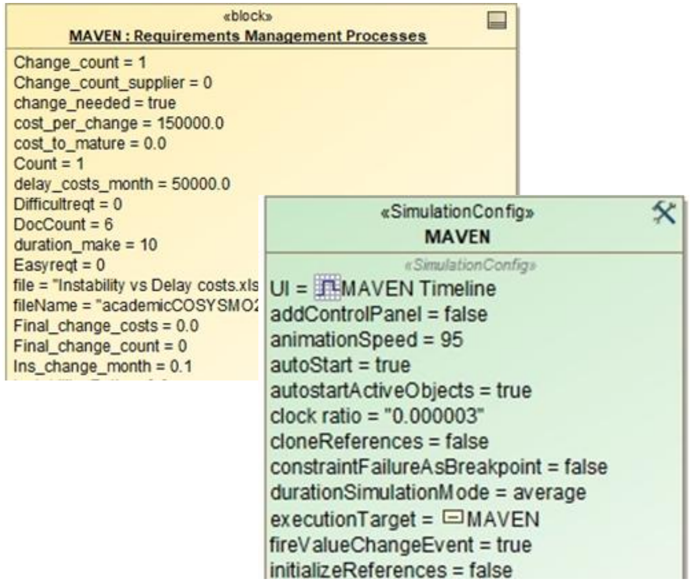
Project	# of System Requirements	Number of Documents	Number of Suppliers	Number of Internal Design Teams
MAVEN	660 (0 of these are rated difficult)	6	6	0
MSL	511 (309 of these are rated difficult)	1	12	22
GOES-R	~1300 (50 of these are rated difficult)	11	9	0
Constellation	~8600 (1220 of these are rated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

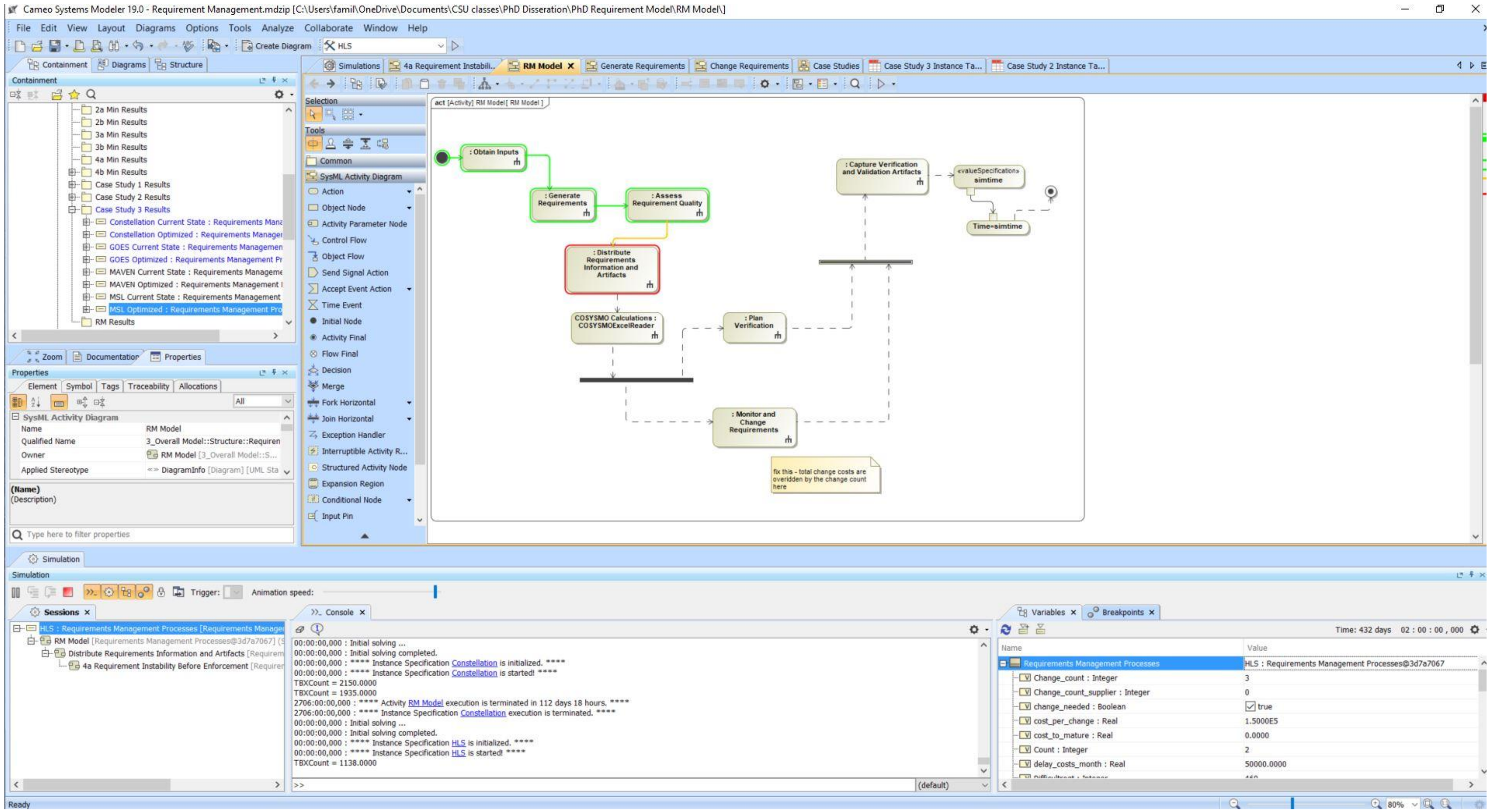
Space Project Assumed Inputs and Case Study Parameter Variation

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.

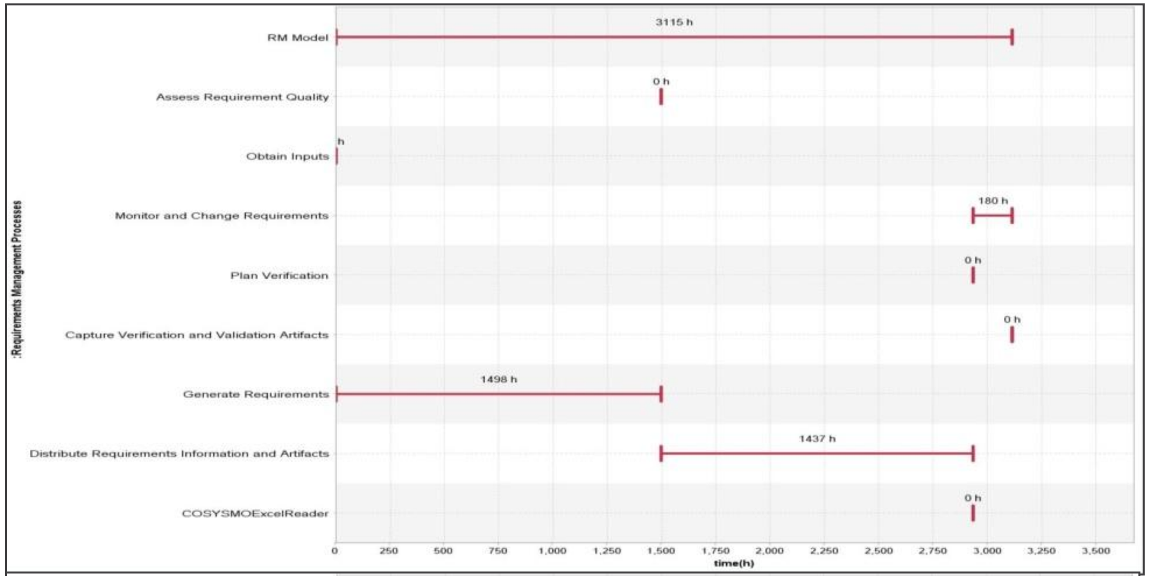


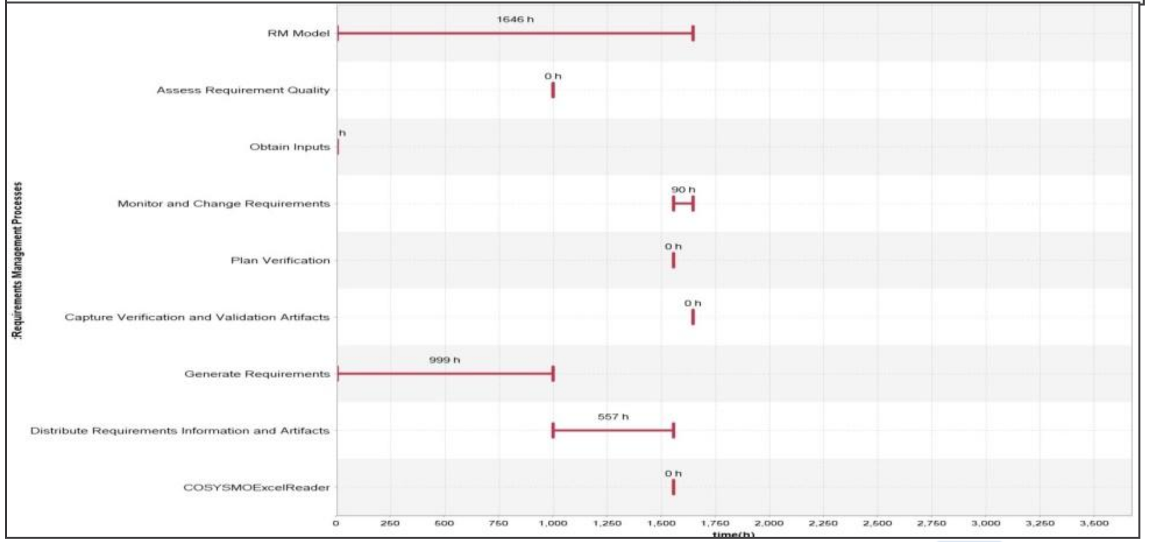


Space Project Case Study Simulation Results

- 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





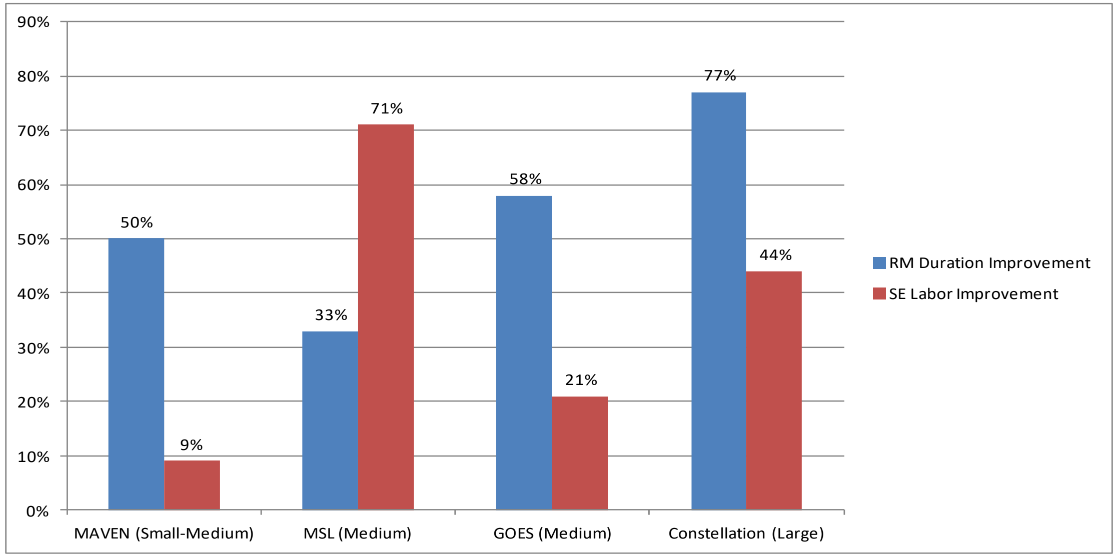
Space Project Case Study Simulation Results

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



Space Project Case Study Total Cost Improvements

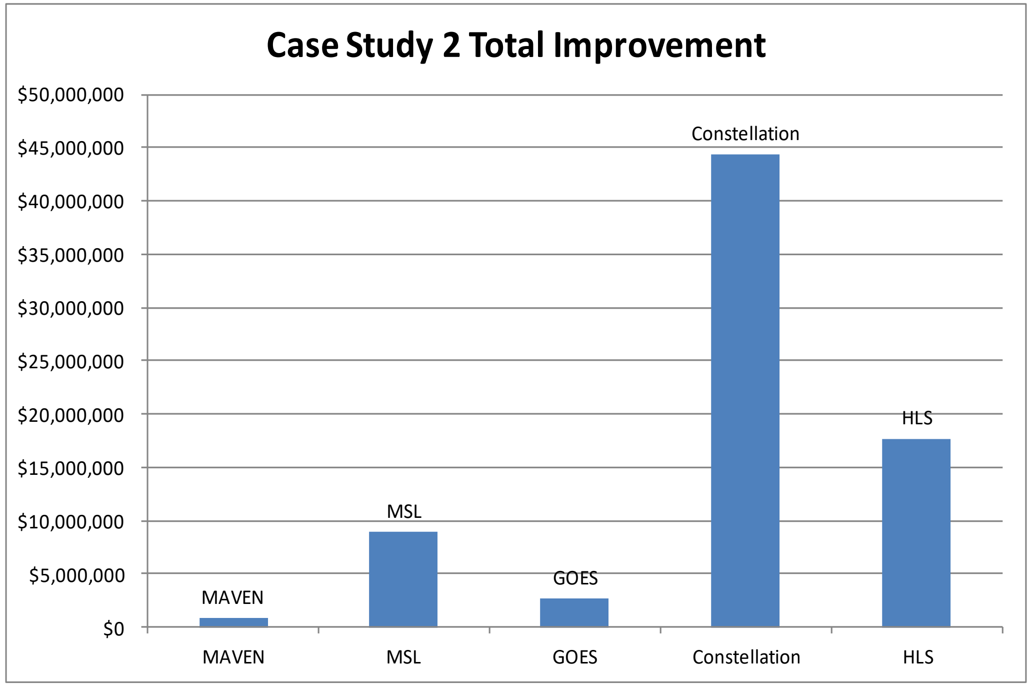
Name	Case Study 1 Total Improvement	Case Study 2 Total Improvement	Case Study 3 Total Improvement
MAVEN	$ 719,359	$ 894,159	$ 1,040,359
MSL	$ 8,776,889	$ 8,950,931	$ 9,097,889
GOES	$ 2,632,300	$ 2,714,021	$ 2,785,300
Constellation	$ 44,173,129	$ 44,347,356	$ 44,494,129
HLS	$ 17,515,748	$ 17,690,966	$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

Space Project 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.



Conclusions on Approach

Utility of Using SysML for Process Evaluation

- When conducting this research a method of assessing process updates was needed that enabled insight into how the updates impact the entire set of processes.

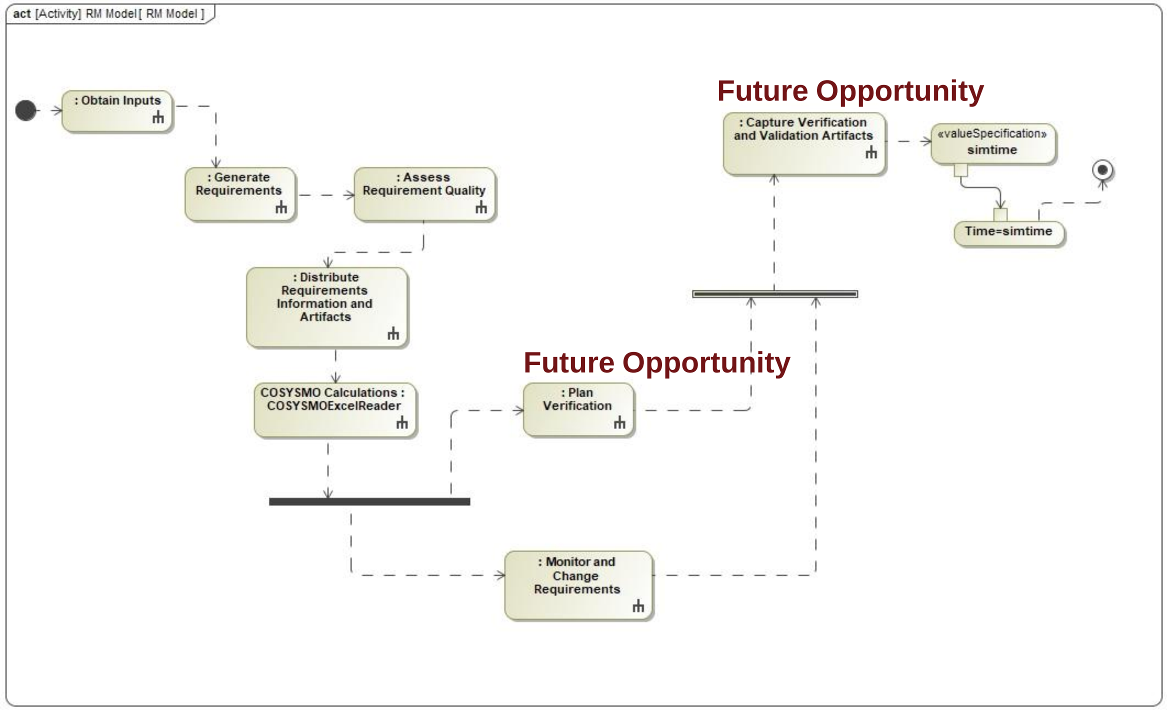
- SysML was used to build an overall process model, set up specific lower processes within it, and change various options of activities and project inputs to see resultant outcomes using an activity simulation.

- It was found this method yielded the desired outcome of insight and data comparison, enabling a visualization of the processes, multiple methods of data calculation, and capture of results that can be further analyzed.

- This method also lends itself to further refinement and study (next slide).

Potential Next Steps for Process Evaluation

- Some considerations for areas of further work include exploring additional cases in the executable requirements management model to assess other parameters, including:
  - Refinement of the project durations with more discrete values obtained from prior programs.
  - More defined inputs for costs associated with incorporation of changing processes for a project or organization (addressing the benefits of change compared to the cost).
  - Further assessment of the other processes within the SysML requirement management model that were normalized to a zero duration during this study.
  - Explore how the recommended requirements management process updates could impact the system verification and validation processes.



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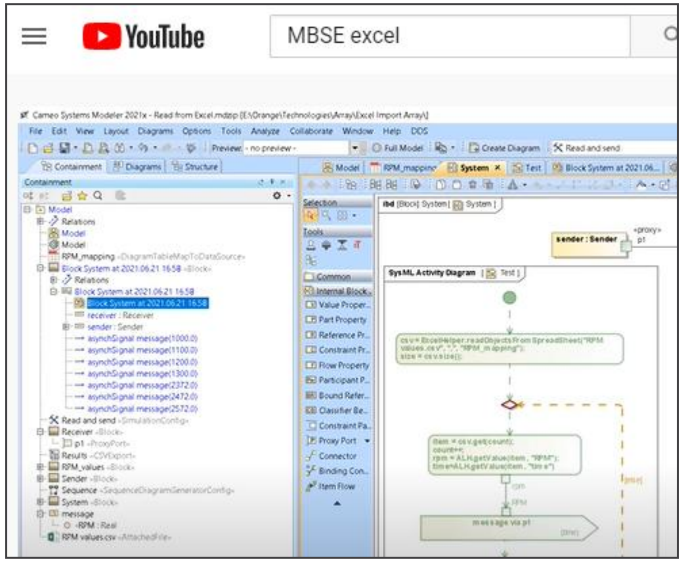
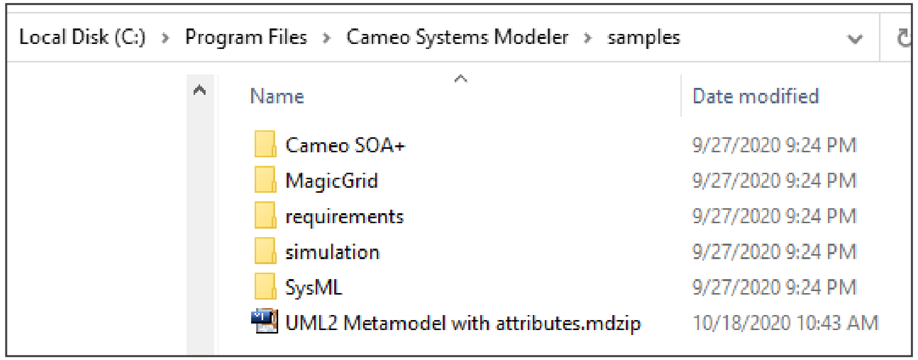
Resources for SysML Simulation

- 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=jk32emTYN4Y and 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.





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