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MIT SDM Capstone Project
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(U) MIT Capstone Project Final Report

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Disclaimer: This report analyzes a hypothetical scenario using systems engineering principles for a graduate course assignment. The opinions are those of the authors and do not necessarily represent the opinions of LLNL, LLNS, DOE, NNSA or the US government.

Introduction and Background

"First Production Unit (FPU) in 5": The National Nuclear Security Administration (NNSA) and upper management at Lawrence Livermore National Lab (LLNL) have set a long-term goal of decreasing the development cycle of new systems to five years or less. The driver is to be able to respond more quickly to emerging situations which require new capabilities. There are numerous approaches to solve the problem, and any single improvement is likely insufficient. We analyzed a variety of possible solutions at varying levels of specificity, as shown in Figure 1, and chose to focus our scope on the optimization of existing documentation processes. We determined that this approach is the least likely to add additional risk and can be accomplished with lower investment than other potential solutions.

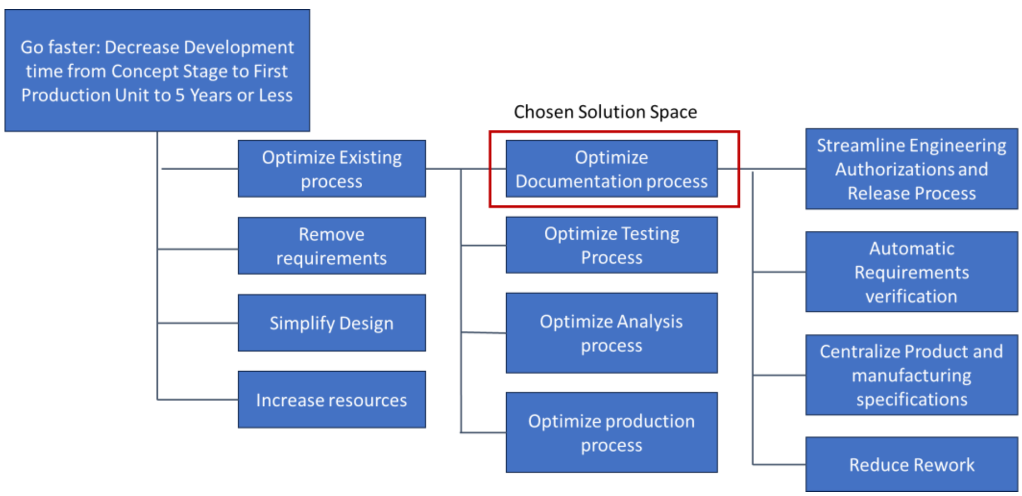

Figure 1 - Possible solution space for decreasing the development cycle from concept to first production unit.

Our capstone project focuses on modernizing the design development processes, production development processes, and communication between design agencies (DAs) and production agencies (PAs) to decrease the timeline from conceptual study to first production unit. To focus our scope, we are looking only at interactions between the DA, Lawrence Livermore National Lab (LLNL), and the PA, Kansas City National Security Campus (KCNSC). Our project's system problem statement (SPS) is below:

> ***TO*** *decrease the time from conceptual study to first production unit* ***BY*** *reducing the DA-to-PA engineering interface complexity* ***USING*** *digital engineering software that centralizes product definition and information exchange protocols.*

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Figure 2 illustrates a functional decomposition of the current design qualification process and defines the boundaries for our proposed system. The formal links to these functions are mostly software programs; the type of software used will vary by product, activity, and organization. There is only one software that is managed across sites to communicate information: PRIME. PRIME is a requirement tracking software used for archiving engineering releases, design definitions, and specifications.

Stakeholder Analysis

Stakeholder Network: The stakeholders and their needs for this system were compiled into the diagram below (Figure 3). The number of stakeholders and the presence of multiple value loops made determining the level of stakeholder importance and need a challenge. We chose to focus on the main groups using and benefiting from the system, and those whose buy-in is needed to successfully implement the system.

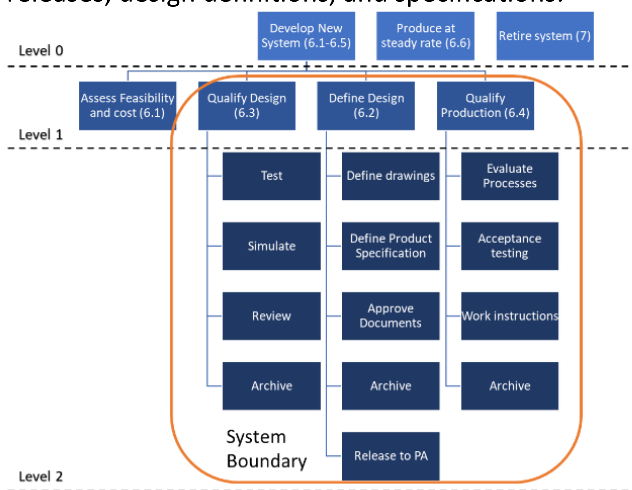

Figure 2 - Functional decomposition of existing system with system boundary defined.

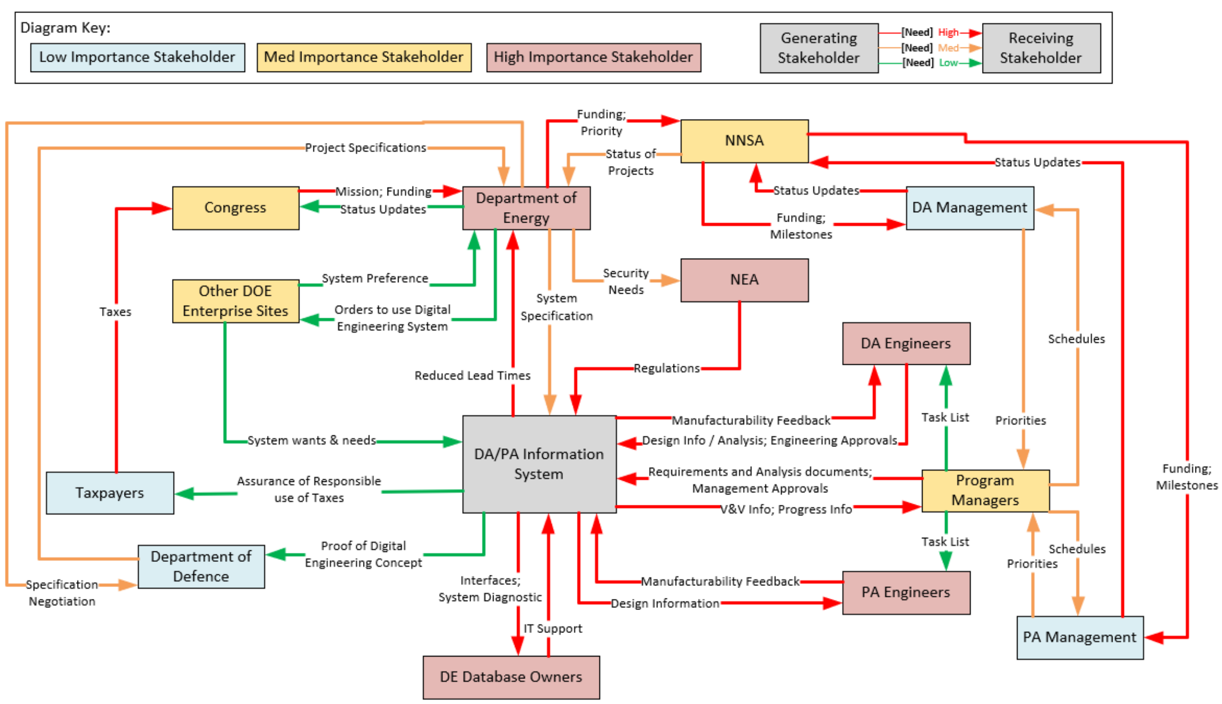

Figure 3 - Stakeholder network for the system

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Metrics: Of the needs of the groups identified, we chose two key metrics to evaluate the system by: schedule reduction and implementation cost. The system needs to reduce the time taken for the DA and PA to settle on a final design and keep implementation costs low to improve adoption rates.

Table 1 - Key stakeholder needs defined and ranked

Need	Need Weight	Need Provided by the System	Performance Metric (units)	Stakeholders Interested in Metrics
1	0.75	**Reduce coordination time between the DA and PA**, therefore decreasing the time to first production unit	Delta in communication and approval effort **(engineer hours/year)**	DOE, DA Engineers, PA Engineers
2	0.25	**Keep implementation costs low** to improve adoption rate	Amortized cost of system over 5 year ROI **($)**	DOE

The weightings were chosen to focus on improving the system coordination time; the cost is less of a factor because of the large potential savings in time and money across the system. The initial cost needed is a factor, as a large barrier to entry will reduce the likelihood of implementation, however, should the ROI be sufficiently, large implementation cost concerns will be greatly reduced or possibly ignored.

There are several high importance needs and stakeholders identified for our system, but most relate to cost or schedule, so the metrics listed above are sufficient to fulfill most of these needs. A high importance stakeholder whose need is not covered by the metrics is the Nuclear Enterprise Assurance (NEA) group with its regulations on security. Our assumption, stated in the next section, is that our system will meet all security regulations, and so it was not factored into the metrics by which we rank the architectural decisions.

We acknowledge that there will be several other needs that are not met by the system within the current scope of what we have set out. One example is that the system misses out on scalability and adoption at other sites. Due to the focused nature of this analysis, solely looking at the LLNL and KCNSC interactions, an analysis for the other 12 NNSA agencies was not performed. Our intent is to use LLNL and KCNSC as a case study for implementation across the DOE enterprise. Traditionally, each site has their own slightly different way of doing things, so we expect this to be a challenge to overcome in the future. That said, our architectural decisions for the system, discussed in the Section below, do not preclude scaling to other sites, it is just outside the scope of this analysis.

Another limitation of our stakeholder analysis is the non-functional requirement that the system be easy to use. The users are high importance stakeholders and if they are not able to use the system easily then there is an increased likelihood that implementation will fail to achieve the desired results. Care should be taken to ensure that "Ease of Use and Maintainability" is an emergent property of the system.

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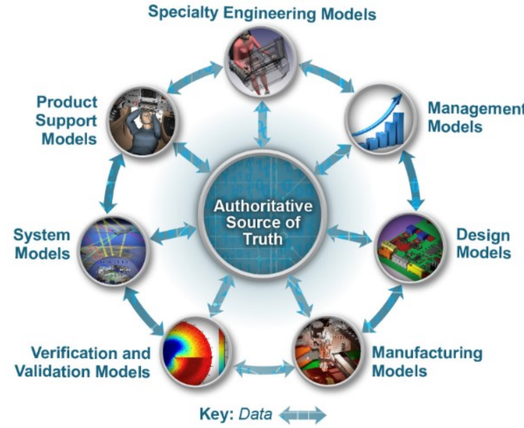
System Architecture Analysis



The Department of Defense and other National Labs are investing heavily in digital engineering and digital twins to advance the capability to supply new systems to stakeholders [1]. Digital engineering provides a centralized source of information integrated with various analysis and design tools. An example of a digital engineering platform is shown in Figure 4. Idaho National Labs demonstrated a 600-day schedule savings with a 25% increase in productivity and an estimated 1.05 billion in losses avoided when they implemented digital engineering tools into their workflow [2]. Multiple industries have demonstrated a direct improvement to schedule deliverables with the implementation of digital engineering on new programs compared to standard processes. According to one meta-analysis published by Mortenson engineering on 18 projects run with Virtual Design and Construction methods there was an average of 25% increased productivity and a resulting 2.95% decrease in overall costs [3]. The potential savings of time and cost are shown to be of great benefit to the FPU development process. We use these case studies as a baseline for our predicted impact metrics in our tradespacae analysis.

We designed a simplified model to assess the impact of our chosen architectural decisions on the time to FPU. Some key assumptions in our modeling approach are:

- Proposed architecture can meet all quality requirements.
- Proposed architecture can meet all security requirements.

We identified 11 work activities that impact the development process and estimated a duration, as well as the number of repetitions of the activity that must occur during the development cycle. Currently, these are treated as serial processes. Dependencies and parallel work should be evaluated in future iterations with higher fidelity estimates. For each of our architectural decision options, we assign an impact factor on the duration of each activity with a scale where 1 is 100% of the original time and 0 is 0% of the original time. Anything over 1 means that the task takes longer than the current system time. We also assign an estimated implementation cost for each decision option. Our tradespace model then calculates the time to FPU by summing the durations multiplied by the repetitions and the impact factor. In the current implementation, we assume that all activities occur serially; future iterations may factor in the effect of dependencies and shared resources. The total cost is the sum of the implementation cost for each decision. A visualization of our model is shown in Figure 5.

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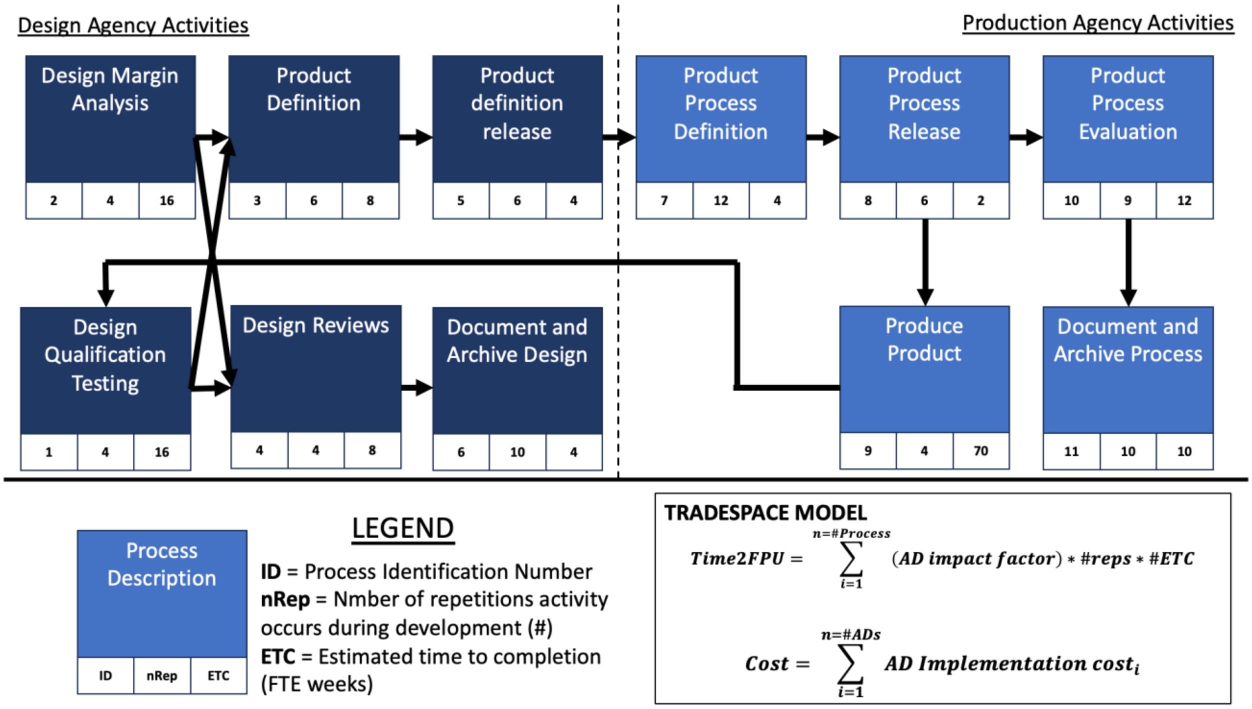

Figure 5 - Simple model for development cycle to FPU

Our architectural decisions and estimated time impact factors and cost are shown in Table 2. For each decision option, the values in the parentheses correspond to (Time Impact factor, cost in $k). The time factors vary between 0.6 and 1.2. We propose that time is saved with various features by reducing rework, eliminating unnecessary steps, and consolidating disjointed data repositories. The only architectural decision with a negative impact (increased time) is the ownership of the software; we assume sharing responsibility or assigning it to a higher governing body increases the complexity and latency in maintaining a streamlined software.

The 5,182 distinct architectures were simulated and the implementation cost and time to FPU were calculated as described in Figure 5. The results are plotted in Figure 6. As anticipated, there are no architectures that will bring the FPU time below the target level; the proposed digital engineering implementation is one of many improvements that will be required to reach the target. The decision that had the largest impact to time was decision ID=7, which was the decision related to the ownership of the software. Our reference architecture corresponds to option 1 of each architectural decision which results in the cheapest option closest to the existing implementation. We use this reference as a baseline comparison for our preferred architecture.

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Table 2 - Architectural decisions and tradespace model inputs (Impact Factor, Implementation Cost) with processes affected as described in Figure 6. Decision options corresponding to our preferred architecture are highlighted in bold..

ID	Decision	Option 1	Option 2	Option 3	Option 4	Processes Impacted
1	Engineering management software used	COTS (0.9,2000)	**COTS + modification (0.8,3000)**	Custom Build (0.85,5000)		3,4,5,6,7,8,11
2	Security Level of information exchange	**Low (0.8,500)**	High (0.9,1000)	Both (0.8,1500)		8,5,7,8,6,11
3	Automatic requirements verification	No (1.0,0)	**Yes (0.8,1000)**			8,5,7,8
4	Cross-Site Standardization	No (1.0,0)	**Yes (0.95,1000)**			5,7,8
5	Type of information exchanged cross-sites	2D Drawing (1.0,0)	3D CAD (0.8,1000)	**3D CAD, notes, tolerances, etc. (0.75,1500)**		5,7,8
6	Level of Granularity of Digital Engineering Model	System (0.9,500)	Sub-system (0.8,2000)	**Component (0.7,4000)**		1,5,7,8
7	Who owns authority of Management Software	**DA (1.0,1000)**	PA (1.0,1000)	Both (1.1,2000)	DOE (1.2,2000)	1,2,3,4,5,6,7,8,9,10,11
8	Built-in Design Analysis Software	No (1.0,0)	**Yes (0.8,1000)**			2,3
9	Approval process for information change/release	Serial (1.0,0)	**Parallel (0.6,1000)**			4,2

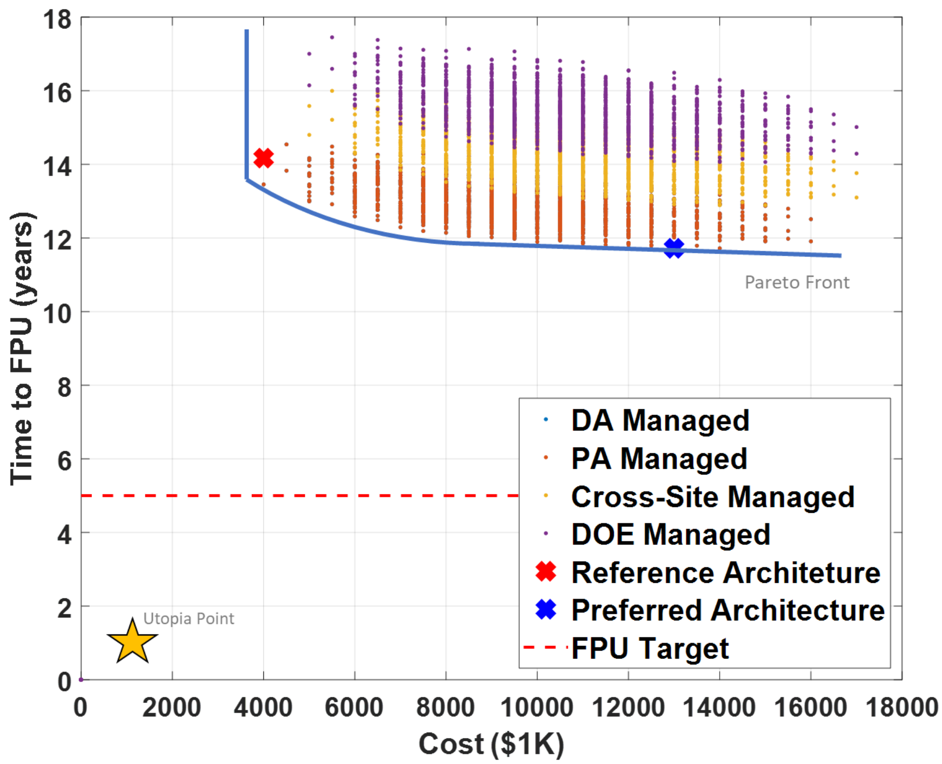

Figure 6 - Architecture Tradespace

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Proposed System Architecture

Our preferred architecture was selected by finding the minimum time to FPU of all the architectures. Our model predicts a decrease in time to FPU by 2.4 years compared to the reference architecture. The decision options corresponding to our preferred architecture are in bold in Table 2. It is worth noting that most architectural decisions for our proposed system do not impact the time it takes to produce parts, which is by far the largest contributor to the overall time, as seen in the Figure 10 in the Appendix. For this project, production improvements are outside of the scope. We recommend using our findings to motivate further study into the impact of reducing the production lead time.

Due to the uncertainties in the current estimates, more work is needed to confirm that this architecture is distinct from other options close in cost and in time. Current model inputs are only estimates and not based on real data or case studies. Factoring in uncertainty, there are likely multiple architectures that have a similar impact magnitude as our preferred architecture. We intend to continue to refine our tradespace model and fully expect our preferred architecture to change as we iterate.

Modeling Uncertainty

More work is required to account for uncertainty in the model used to generate the architecture tradespace (shown in Figure 5). This uncertainty would be added by generating probability density functions (PDFs) for each architectural decision option and the activities that define the project. The PDFs would be refined by further researching the influence each architectural decision had on the duration and cost of the project; information for this research may be gathered through historical analysis, interviews with stakeholders, and market comparisons.

A starting point to define the uncertainty associated with the project activities could be the project's baseline schedule, which will provide the estimated durations of each project. Because it is unlikely that each activity will follow the baseline schedule, PDFs should be assigned to the activities to account for the possibility of them finishing late, or early. These PDFs could be based on similar historical activities that have been completed; the variance in schedule of these activities will provide a basis for creating probability functions.

Adding uncertainty to the activities would require adding an additional layer of complexity to the model: accounting for the order of the activities, which currently has no effect within the model. Activity order would begin to matter once you add uncertainty because an activity that completes late would affect subsequent activities. Adding dependencies between activities, such as start and finish time, would be a required addition to the model to perform a Monte Carlo simulation.

Once the uncertainty for both the project and architectural decisions are defined, a tradespace may be generated that includes uncertainty bands for each possible tradespace. This additional layer of information will help our team choose between optimal architectures. It is possible that we discover our preferred architecture from before performing this analysis has a lot of uncertainty associated with it, causing us to shift focus to different architectures that rank similarly but are more certain in their performance.

As mentioned previously, time to FPU is weighted more heavily than cost, i.e., cost is not as large a deciding factor for a preferred architecture, time reduction is the dominant key indicator.

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Because of this, the uncertainty associated with the time to FPU will be considered more than that of cost.

System Complexity Comparison

In addition to the tradespace, we assessed complexity using methods described in the next Section of this report. The preferred architecture has a complexity score that is 49% lower than the baseline score. The benefits of consolidating separate software programs and databases will improve efficiency in the development process in the long term.

The complexity analysis was performed by taking the formal decomposition of the baseline (current) system and the proposed digital engineering system and converting them into Design Structure Matrixes (DSM). The DSM were then processed using two major equations and an evaluation of the resulting node diagram to determine the overall Structural Complexity. Structural Complexity **C** is derived by calculating the Component Complexity C_1 and adding it to the product of the Pair-wise component interactions C_2 and the Topological complexity C_3. Thus $C = C_1 + C_2 * C_3$

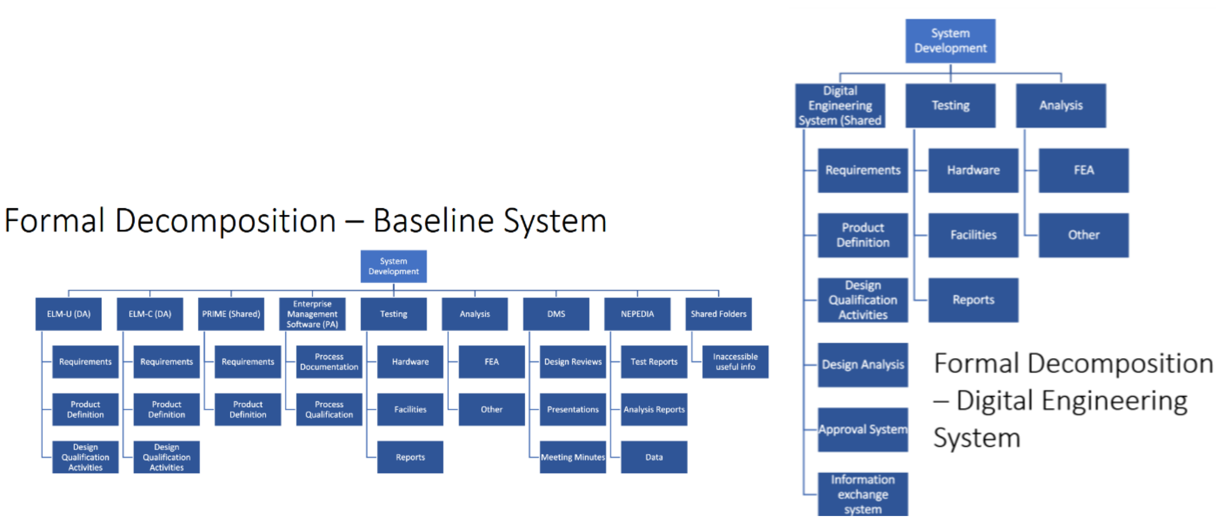

Figure 7 Systems Formal Decomposition of both the Baseline and Proposed systems

C_1 is composed of $\alpha+\beta*(\gamma/\alpha)$ where alpha (α) is the number of items within the decomposition, beta (β) is number of interactions between the items, and gamma (γ) is the sum of the singular value decomposition (SVD) values from the DSM. This determines the component complexity of the system.

C_2 is determined by taking the greater of the number of component-component interactions or the average magnitude of said interactions. In this case since the DSM is already a unit matrix the average magnitude is less than 1 so the number of component-component interactions is used.

C_3 can be calculated using system graph energy, however, per the presentation Rebentisch, Eric, (March 1, 2023) Foundations of System Design and Management III, System Design and Management, MIT. It is possible to substitute the calculation with a rough order constant based upon the systems visual complexity utilizing a Node Diagram as in Figure 8. As a Hierarchical structure the systems are assigned a value of 1.5 for topological complexity.

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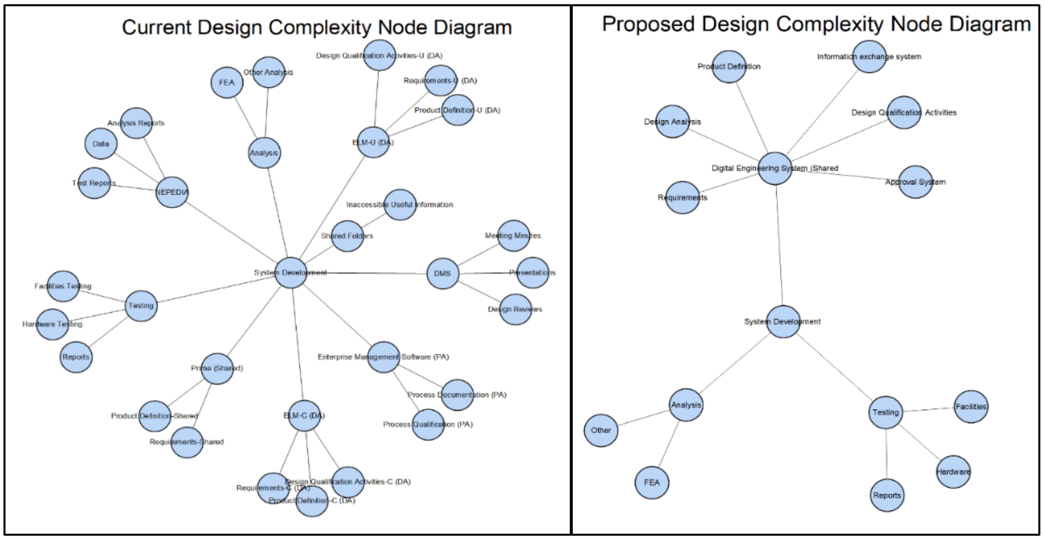

Figure 8 - Current vs Proposed Design Complexity Node Diagram

These numbers are summarized in Table 3**Error! Reference source not found.**. The baseline design generates a complexity score of 232, which the proposed design generates a score of 114. This allows us to conclude that the proposed design is approximately half (49.13%) as complex as the original design. As complexity is inversely proportional to speed and accuracy within an organization by reformatting the information exchange between the DA and PA there is potential for significant savings.

Table 3 Design complexity comparison

	Component Complexity	Interaction Complexity	Topological Complexity		Structural Complexity
	C1	C2	C3		Total C
Baseline	91.11	94	1.5		232
Proposed	49.88	43	1.5		114

Conclusion

Although our proposed architecture does not meet the long-term goal of FPU in 5, we demonstrated that incremental process optimizations can have a substantial impact on the length of the development cycle. Of the design options evaluated, an 18% time savings may be realized by switching to a centralized digital engineering platform, decreasing the FPU time from approximately 14.1 years to 11.7 years. Adding architectural decisions may increase this estimate. We acknowledge that, as of now, our uncertainty is high; we will continue to iterate on our tradespace model and factor in more realistic cost and time estimates by looking at previous case studies in the same or similar industries. In addition to our tradespace analysis in cost and time space, we performed a complexity analysis on the formal architecture of our proposed solution compared to the current implementation and found that the preferred architecture has a lower complexity primarily due to the consolidation of different software programs and databases. Prior to deciding on a final architecture, we propose continuing to iterate on our defined approach by allocating one full-time system engineer for three months.

References

[1] Office of the Deputy Assistant Secretary of Defense for Systems Engineering, "Department of Defense Digital Engineering Strategy," Washington, DC, 2018.

[2] C. Ritter and A. Todd, "Digital Engineering," Idaho National Laboratory, 2021. [Online]. Available: https://inl.gov/digital-engineering/. [Accessed August 2023].

[3] Mortensen Engineering, "THE IMPORTANCE OF VIRTUAL DESIGN & CONSTRUCTION VDC-DRIVEN OUTCOMES," Mortensen, July 2014. [Online]. Available: https://www.mortenson.com/-/media/project/mortenson/site/files/services/vdc/study/the-importance-of-virtual-design-and-construction---mortenson-construction.pdf.

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Appendix

The flowchart below is a detailed description of the product definition process covered at a high level under Define Design (6.2) in Figure 9. The process covers only the design agency side of the product release process.

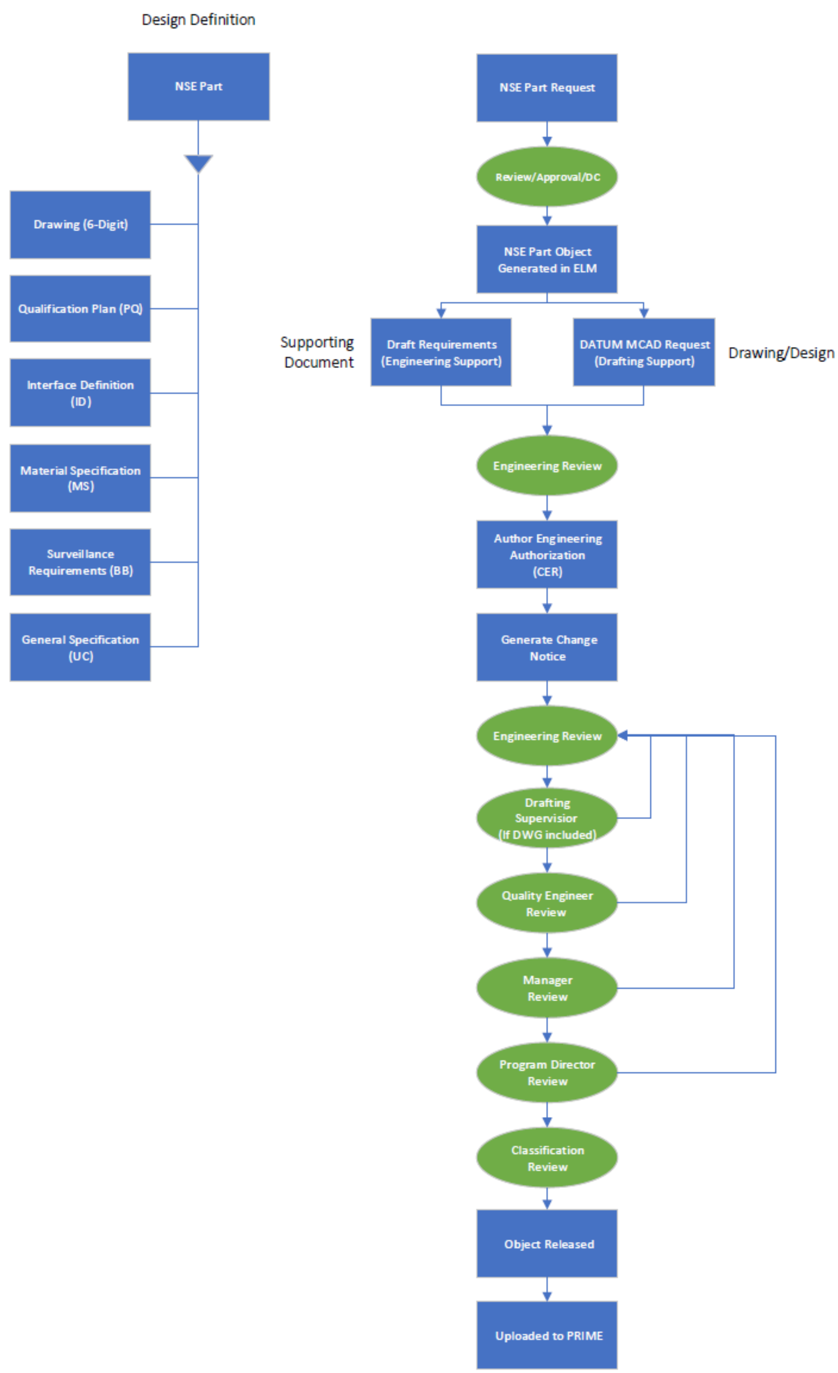

Figure 9

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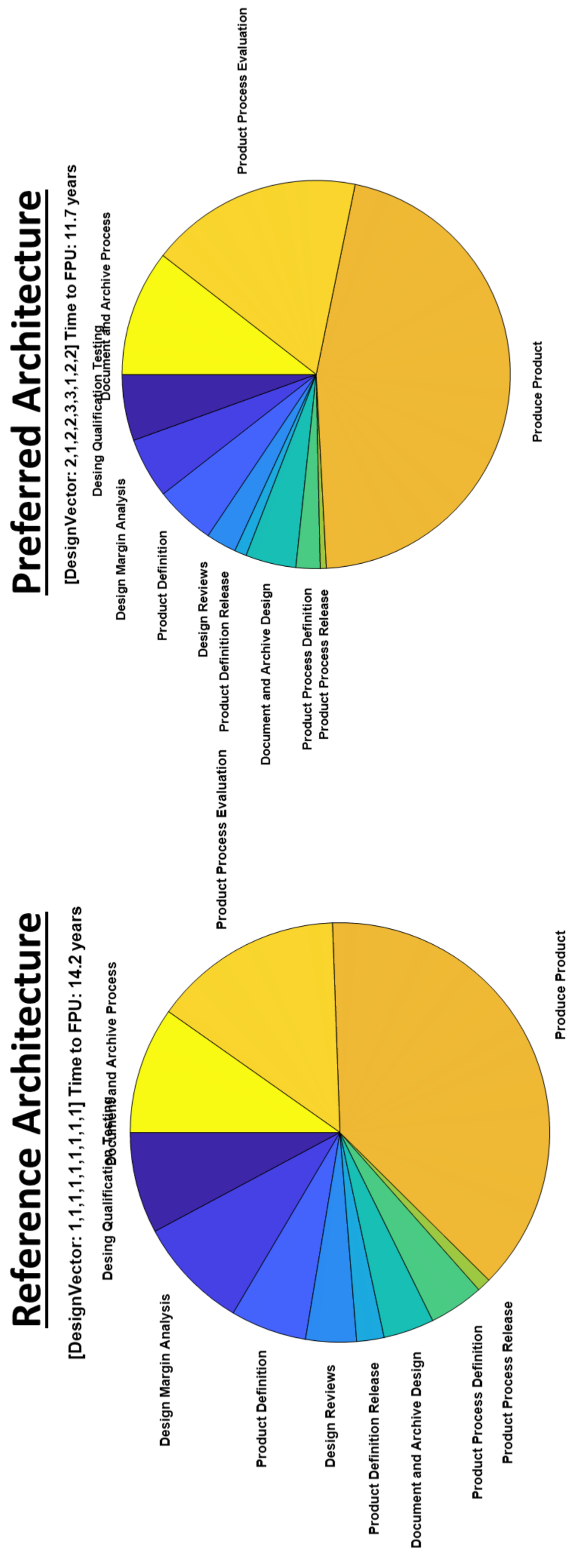

Figure 10 – Distribution of time spent progressing to FPU

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