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Abstract

The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) operates one of the most advanced laser systems in the world, relying on a vast number of optical components and Line Replaceable Units (LRUs) to maintain its functionality. Over time, these components degrade due to operational wear, necessitating refurbishment to sustain performance. However, many NIF LRU refurbishment factories have been "mothballed" or suffer from aging infrastructure, inconsistent work flows, and inefficiencies due to different approaches to production control and management. This paper explores the concept of reference architecture as a standardized framework to guide the redevelopment and restructuring of NIF LRU refurbishment factories. By establishing a common reference architecture, the refurbishment process can achieve reduced inefficiencies, produce quality products, and enhanced coordination across factories. This paper evaluates existing reference architectures, particularly those that integrate technical architecture, business architecture, customer context perspectives, and proposes tailored reference architecture for NIF LRU refurbishment factories.

1 Introduction

The National Ignition Facility is the world's most precise and reproducible laser system. It precisely guides, amplifies, and focuses 192 powerful laser beams into a target about the size of a pencil eraser in a few billionths of a second, delivering more than 2 million joules of ultraviolet energy and 500 trillion watts of peak power. NIF generates temperatures at the target of more than 180 million degrees Fahrenheit and pressures of more that 100 billion Earth atmospheres. Those extreme conditions cause hydrogen atoms to fuse and release energy in a controlled thermonuclear reaction. NIF's unique energy and power enable cutting edge research to help keep America safe and secure, explore new frontiers of science, and lay the groundwork for a clean, sustainable source of energy. [1]

A remarkable number of optical components and Line Replaceable Units (LRUs) make up NIF's infrastructure. There are more than 7,500 meter-sized optics and 26,000 smaller optics. [2] There are over 40 different LRU types in NIF. Many of these LRUs are high precision electro-mechanical assemblies. Sketches of many of these, along with their locations in the beamline, are shown in Fig. 1. [3] Each of these optics and LRUs require occasional repair and maintenance due to NIF running past the damage threshold of optical materials. Due to this operational wear, NIF runs optical and LRU refurbishment factories to keep the worst damaging optics and LRUs in working order. However, critical LRU factories are approaching 40 years of age, and some have been completely "mothballed" due to low maintenance requirements of their LRUs. Over the past several years, NIF has started to see that many less damage prone optics and LRUs are degrading in performance due to deferred maintenance, obsolescence, and aging. This increases the risk of a significant stoppage or slowdown in experimental operations.

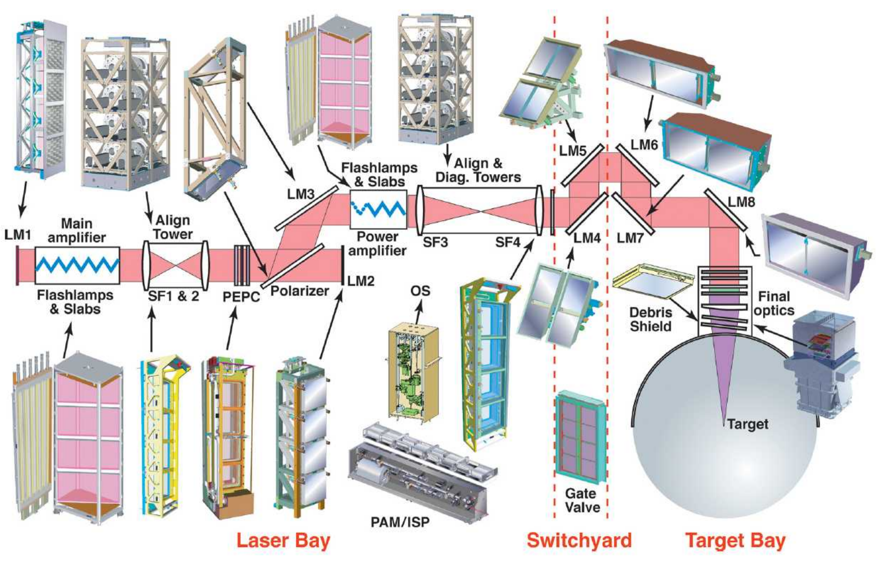

Figure 1: Line replaceable units are the optics building blocks of NIF.

To ensure that NIF continues to deliver on key experimental campaigns, a systematic review was undertaken of the entire NIF enterprise. This review identified key issues that would need to be addressed to sustain NIF. One of these key initiatives is to restart or upgrade numerous optics and LRU refurbishment factories across the directorate. This scope has been spread across multiple groups and disciplines. There are two key observations from the work that has been completed so far to bring these factories back online. One, documentation of the original system architectures of each factory has been sparse and vague. And two, the teams that are working to bring these factories back online are well engineered, but slightly different ways to decompose their system architectures. This has resulted in cross-factory interface inefficiencies, quality control issues, and system integration conflicts. Due to the increased scope size and integration dynamics between factories, a common reference architecture would help resolve these issues by managing synergy between factories, providing guidance on architecture principles, architecture baselines, and capturing architectural patterns. [4]

2 Leveraging Existing Reference Architectures

2.1 Reference Architecture Definition and Development Principles

Reference architecture is a standardized framework, or blue print, that provides a predefined set of best practices, guidelines, and structures for designing and implementing systems within a specific domain. Additionally, reference architecture is an elaboration of company mission, vision, and strategy. Such reference architecture can facilitate a shared understanding across multiple products, organizations, and disciplines about current architecture and future directions. [4] As seen in Figure 2, each organization, or in this case LRU factory, will implement the same mission, vision, and strategy. This reduces the time spent redeveloping these components for current and future systems as well as aligning each factory's core values.

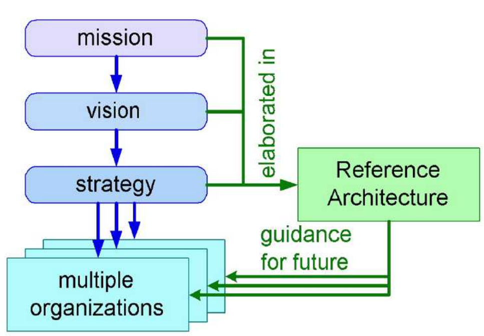

Figure 2: Organization mission, vision, and strategy is elaborated in the Reference Architecture and is received as guidance for future systems.

For reference architecture to be fully defined, it should address the technical architecture, business architecture, and customer contexts. If system context is not complete, the reference architecture would represent solutions for unspecified problems in unspecified contexts. [4] Often times, NIF LRU factories focus on technical architecture and do not assess the business architecture and customer context thoroughly. Not including the business architecture could result in a lack of funding flow, staffing, or late critical path deliverables. If the customer context is not included, the factory could produce LRUs that don't meet all stakeholders' acceptance criteria. Figure 3 shows how all three aspects of reference architecture provide relation guidance to each other which results in fully defined reference architecture.

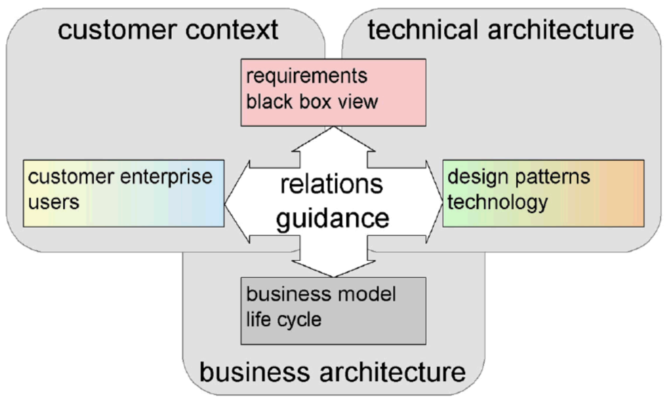

Figure 3: Contextual relationship between business architecture, technical architecture, and customer context. All three influence each other and drive system requirements.

A reference architecture is based on concepts proven in practice. Most often, preceding architectures are mined for these proven concepts. [4] From these proven architectures, patterns are uncovered by gathering implicit and explicit knowledge from those that developed it. For NIF LRU factories, interviewing individuals who originally designed and built the factories would help find beneficial patterns and pitfalls in their system architectures. Asking for any formal explicit documentation produced during that time would also be useful to understand how each factory operated. By incorporating these patterns into the reference architecture, systems developed from it will have higher rates of success and intentionally deviate from past mistakes. An additional resource for developing a reference architecture is to leverage existing reference architectures from external entities. This resource can be used to refine and compare the LLNL LRU factory reference architecture, while also pointing out important functions that may have been missed.

2.2 Existing Reference Architectures

As mentioned in the previous section, it is critical to include the business architecture, technical architecture, and customer context in reference architecture. After an evaluation of these aspects for NIF LRU factories, it was determined that a reference architecture that focuses on the business and technical lifecycle of the factory would be the best fit. This is due to the similarities between technical and administrative activities across each factory but vastly different customer NIF LRU requirements. However, there are customer interfaces that should be included such as requirement verification plans, transport, handling, and storage. Additionally, presenting the relations between technical and administrative functions would provide a roadmap for individuals that primarily have an engineering background and not a business or production background. The National Institute of Standards and Technology (NIST) published a paper titled "Reference Architecture for Smart Manufacturing" that partitions the reference architecture based on the technical and business lifecycle of a system. The reference architecture described in this paper meets the NIF LRU factory class of systems' needs.

2.3 Evaluation of existing reference architectures

The reference architecture presented in "Reference Architecture for Smart Manufacturing" (RASM) describes the principle technical and business activities involved in the engineering and production activities of a manufacturing enterprise engaged in the production of complex electro-mechanical products. [5] RASM was developed by NIST experts drawing extensively on previous manufacturing factory projects. The overall view maintained in the RASM reference architecture is that of the engineering or production manager responsible for assigning tasks and ensuring that the results of on task are provided to another. [5] Thus, ensuring that the architecture functions run smoothly. The primary domain of the RASM reference architecture is the manufacturing of assembled products and subassemblies. The architecture is intentionally left at a relatively abstract level to allow factories to be flexible enough to accommodate a variety of product variants.

The value to the RASM reference architecture, shown in figure 4, comes from its detailed functional decomposition that characterizes the key inputs and outputs between functions. It also decomposes the architecture that follows the general phases of product development and production system. This is similar to the way project phasing is done at LLNL. In Figure 4, the A0 “Realize Product” function is decomposed into, A1 “Design Product”, A2 “Engineer Manufacture of Product”, A3 “Provide Production Resources”, and A4 “Produce Products”. Each first level function is then broken down into second level functions. The IDEF0 model of this architecture acts as a road map that can be traced to identify deliverables and work flows. Most of the first level functions and inputs and outputs are considered in LLNL developed factory architectures. However, some of the second level functions are overlooked or ignored which can lead to inefficiencies due to an underdefined factory system.

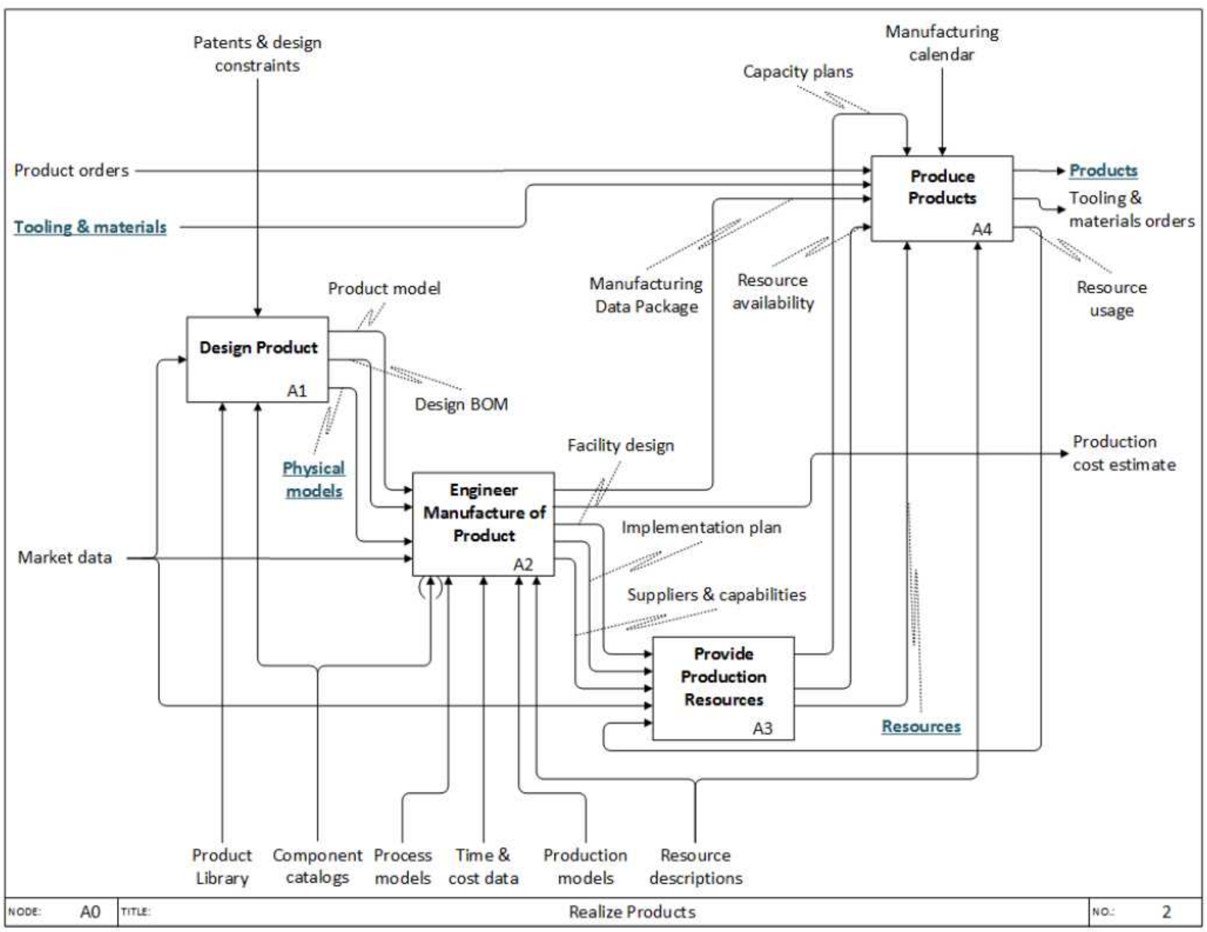

Figure 4: Contextual relationship between business architecture, technical architecture, and customer context. All three influence each other and drive system requirements.

3 Development of a Reference Architecture for NIF LRU Factories

3.1 NIF LRU Factory Mission Statement

The NIF LRU factories realize LRU designs by providing product designs, production facility engineering, production resources, and fabricated products. These services are provided to maintain and upgrade NIF to aid experimental campaigns in support of NNSA's and LLNLs Stockpile Stewardship programs. The NIF LRU factory's main role is to effectively and repeatably produce quality NIF LRUs. This includes interfacing with customers to gather LRU design expectations and requirements, designing and building LRU factories that are in accordance with the NIF safety basis, providing quality training to internal and external factory personnel resources, and ultimately maintaining the capability to produce LRUs that are calibrated and acceptance tested. The NIF LRU factory's job is not complete until the product is installed on NIF can operationally qualified. An LRU design and quality feedback loop is expected to be maintained between the factory and the NIF facility. In the event of online problems, the factory staff is expected to act as subject matter experts that can aid the disposition and root cause analysis of LRUs.

3.2 NIF LRU Factory Vison

The NIF is a world-class organization that proactively leverages its multi-billion-dollar assets to ensure that premier science experiments are accomplished in a reliable, safe, and cost-effective environment. NIF's LRU factories, which support NIF's vision, are professional, disciplined, offer outstanding high precision LRU designs, and produce them with quality workmanship repeatably. All work completed by NIF LRU factories meet Department of Energy (DOE), LLNL, and state requirements. NIF LRU factory staff are exceptionally well trained, technically excellent, inquisitive, and constantly striving for improved performance and technical results. The team environment and aggressive technical challenges promote professional growth, staff retention, and an esprit de corps as the team heads towards history-making experimental results. The team's core values maintain that all activities are performed safely, with quality, respect toward co-workers, and with integrity. [6]

3.3 Functional NIF LRU Realization Model

3.3.1 Functional Decomposition

Figure 5 shows the functional decomposition of the F0 "Realize LRU Products" function provides a structured breakdown of the key activities required to engineer the LRU design, develop the manufacturing process, allocate resources, and manufacture LRUs. By organizing the process into discrete and actionable functions, the decomposition offers a clear framework for understanding the roles, responsibilities, and interactions within the LRU manufacturing lifecycle. This modular architecture supports both a phased and scalable approach to project implementation. Additionally, this modularity allows particular functions to go dormant when their nonrecurring engineering (NRE) work is complete and reactivated if a new LRU product is requested by the customer. Note that only F.2 through F.3 were decomposed to their second level since LLNL already has a robust product design and review reference architecture.

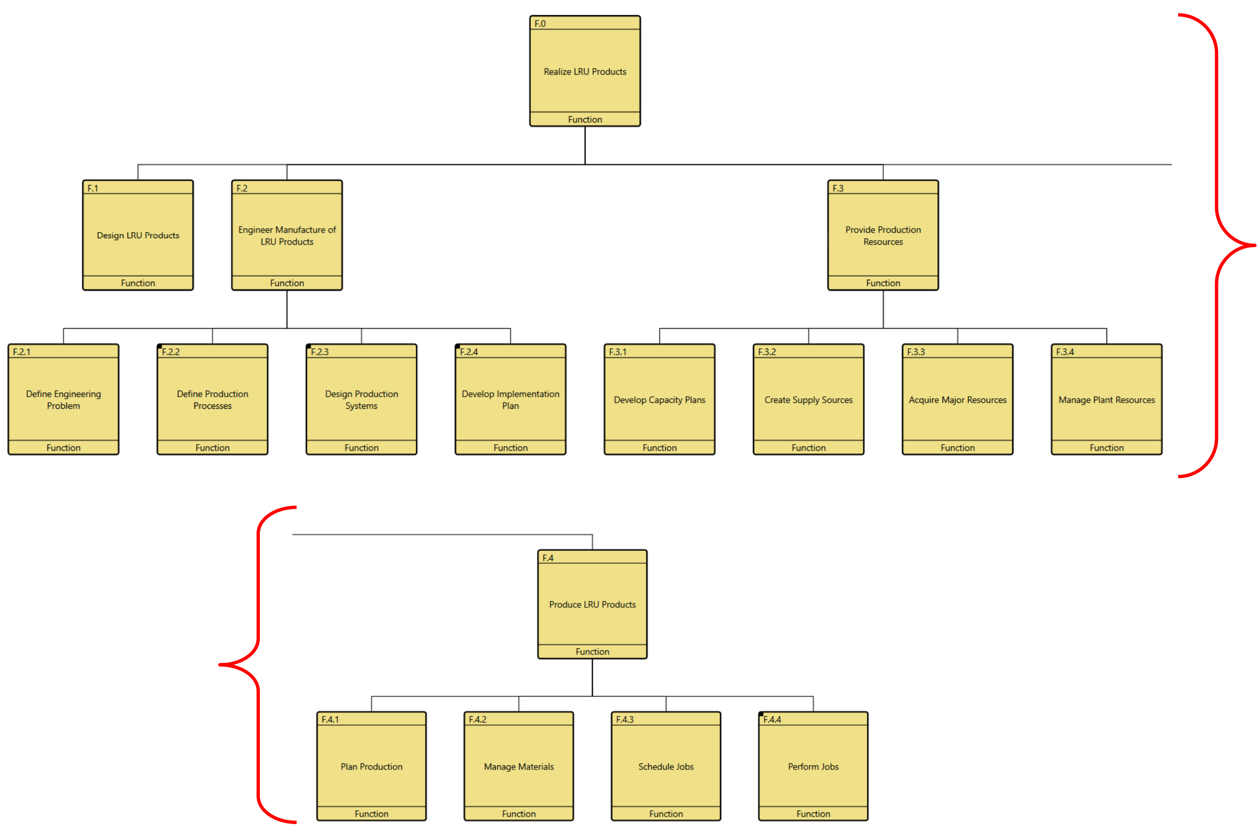

Figure 5: Functional hierarchy of F.0 "Realize LRU Products. F.1 was not decomposed since LLNL already has a robust product design and review reference architecture

3.3.2 First Level Functional Decomposition

Figure 6 shows the first-level decomposition of the "Realize LRU Products" function. At this level, the reference architecture reveals several key trends that reflect phased and scalable approach realizing LRU products. A prominent trend, that will also be seen in lower-level decompositions, is the progressive flow from concept to execution. This waterfall structure emphasizes a reliance on thorough planning and front-end definition before execution begins. DOE regulations usually require the project scope and cost to be well known before funding is fully awarded. This architecture conforms to this standard. Another noticeable trend is the scalability. For example, if a specific factory needs to produce multiple LRU designs, F.1 "Design LRU Products" could be composed of several design tasks. The inputs and outputs from F.1 would not change. However, the information transferred between functions would be more substantial.

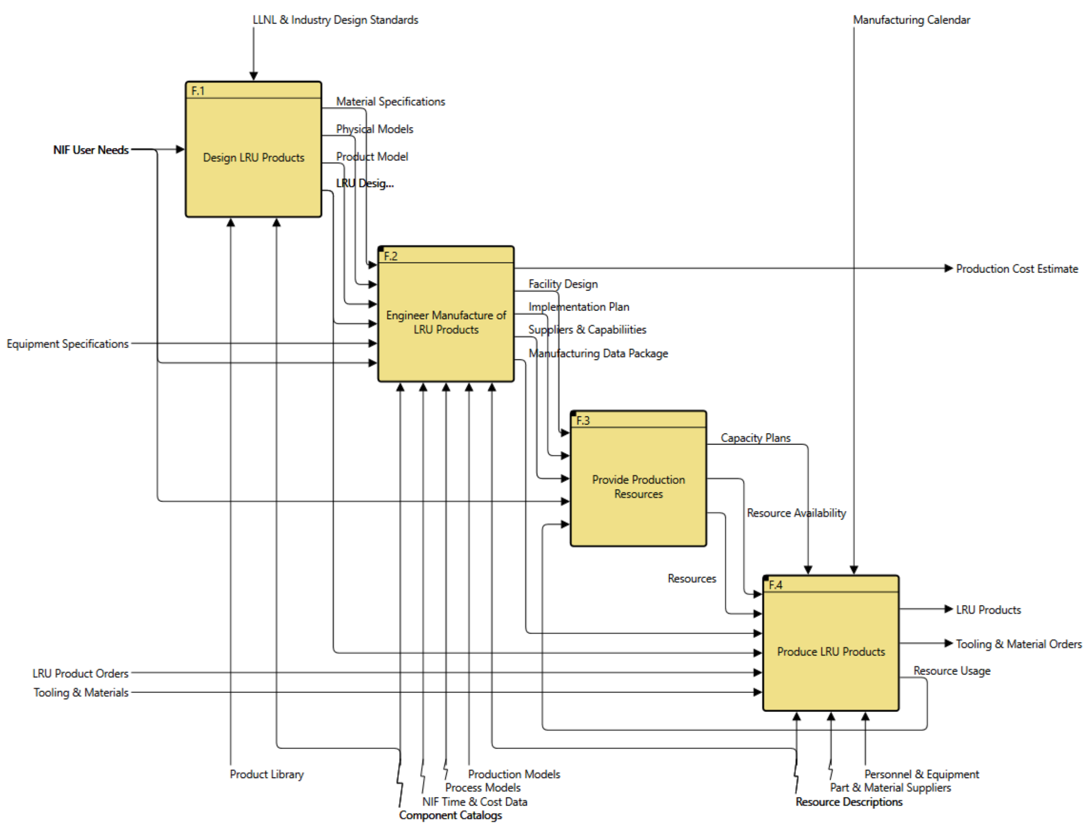

Figure 6: Functional decomposition of F.0 "Realize LRU Product"

3.3.3 Second Level & Third Level Functional Decompositions

For the purposes of this discussion, F.2 "Engineer of Manufacturing of LRU Products" will be decomposed to its second and third levels. In the appendix of this paper, functions F.3 and F.4 are also decomposed further. A common trend that can be seen in the second level and third level decompositions of this reference architecture, shown in Figure 7 and 8, is the emphasis on data driven decision making. The functions that define the production process require many inputs to produce their outputs. This allows for well-informed decisions on critical components of the factory. These decompositions also show that information is regularly distributed to multiple functions and occasionally have recursive relationships. This communication helps the organization as a whole maintain the same vision of the product they are producing and speeds up product refinement. With the reference architecture decomposed to the second and third levels, which also defines the key information transferred between functions, an LLNL team developing an LRU factory would have a clear and systematic way to meet stakeholder requirements.

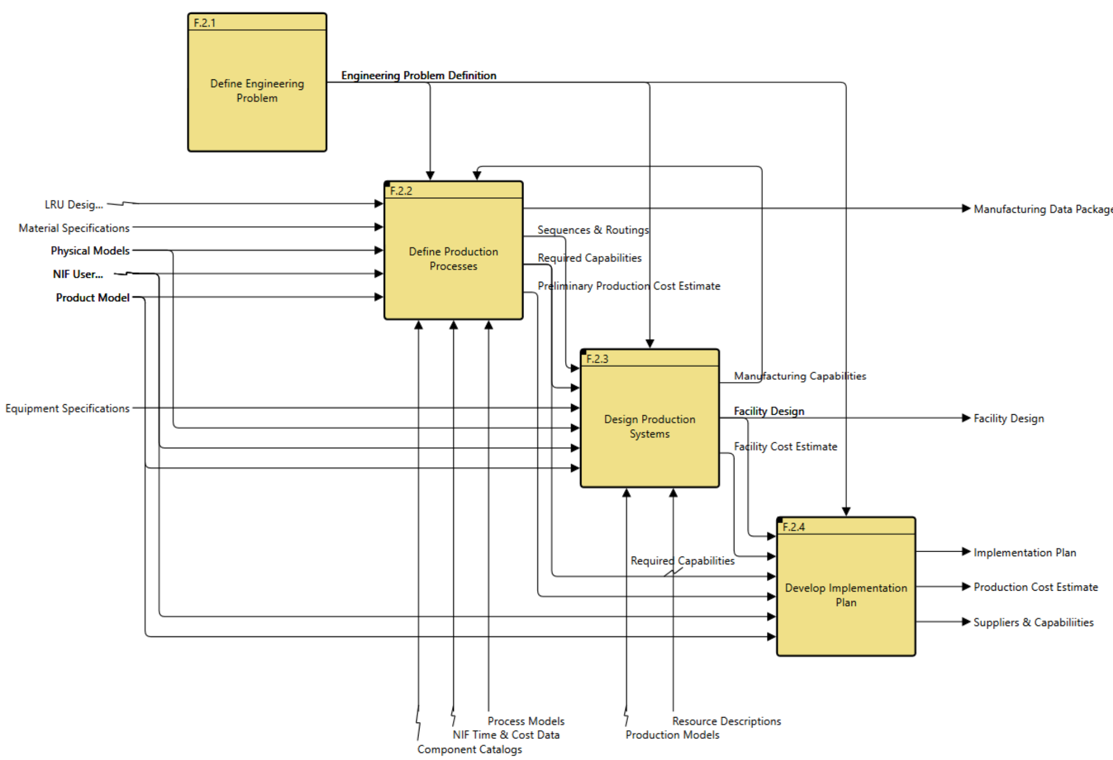

Figure 7: Functional decomposition of F.2 "Engineer Manufacture of LRU Products"

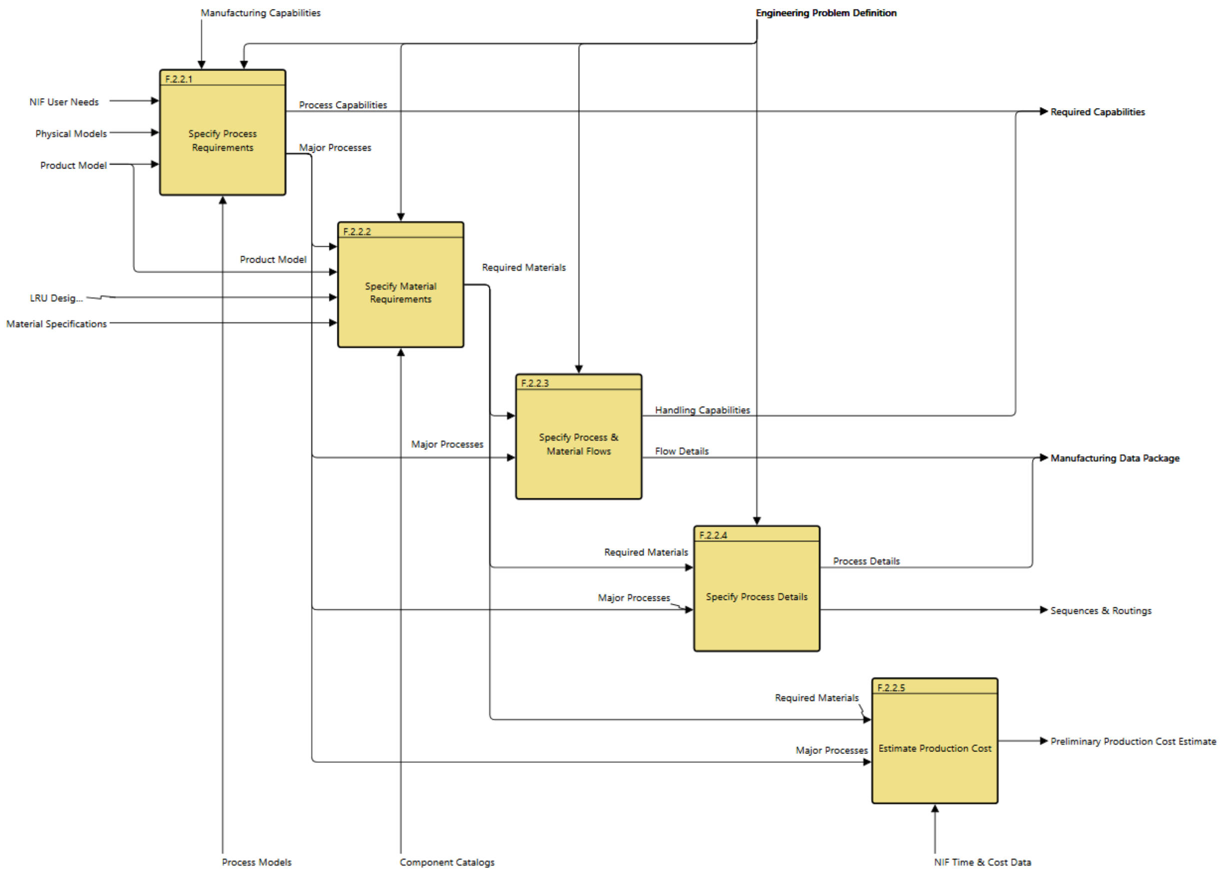

Figure 8: Functional decomposition of F.2.2 "Define Production Process"

4 Evaluation of the Proposed Reference Architecture

There are several areas that the proposed NIF LRU factory reference architecture could improve. This reference architecture has many interconnecting functions that require a large quantity of inputs. If these functions are not closely managed by a project engineer, or someone completely dedicated to this role, some functions or even the resulting product could underperform. Perhaps consolidating common inputs or outputs that result in a data package would be more efficient and easier to track. Additionally, F.4 "Produce LRU Product" does not currently have a quality control function. Although, the manufacturing data package should include product test plans, there is no output from the "Perform Jobs" function (Figure 15) that feeds into a quality control function. This could result in LRUs that are sent to NIF that don't meet requirements. Overall, this reference architecture gives users a clear baseline of how a NIF LRU factory system architecture should function. Some of these lower-level details should be left to the user to define further.

5 Conclusion

In conclusion, the implementation of a reference architecture for NIF LRU refurbishment factories is a critical step toward addressing the operational inefficiencies and inconsistent work flows currently faced by LLNL LRU factories. By adopting a reference architecture that integrates technical architecture, business architecture, and customer context, LLNL can enhance coordination across its factories, improve product quality, and streamline workflows. The proposed reference architecture presented in this paper was based on lessons learned from previous LLNL factory development projects and principles from existing reference architecture models. The resulting reference architecture provides a phased and scalable approach that can adapt to the evolving needs of the NIF facility. If this reference architecture is put into practice, continuous evaluation and refinement will be needed to address new challenges discovered during factory development projects and inform the next NIF LRU factory project. Ultimately, the proposed reference architecture will be a valuable resource for NIF and the staff that work so hard to maintain its world leading laser performance.

6 Appendix: Further IDEF0 Functional Decomposition Diagrams

First Level Decomposition of F.0 "Realize LRU Products"

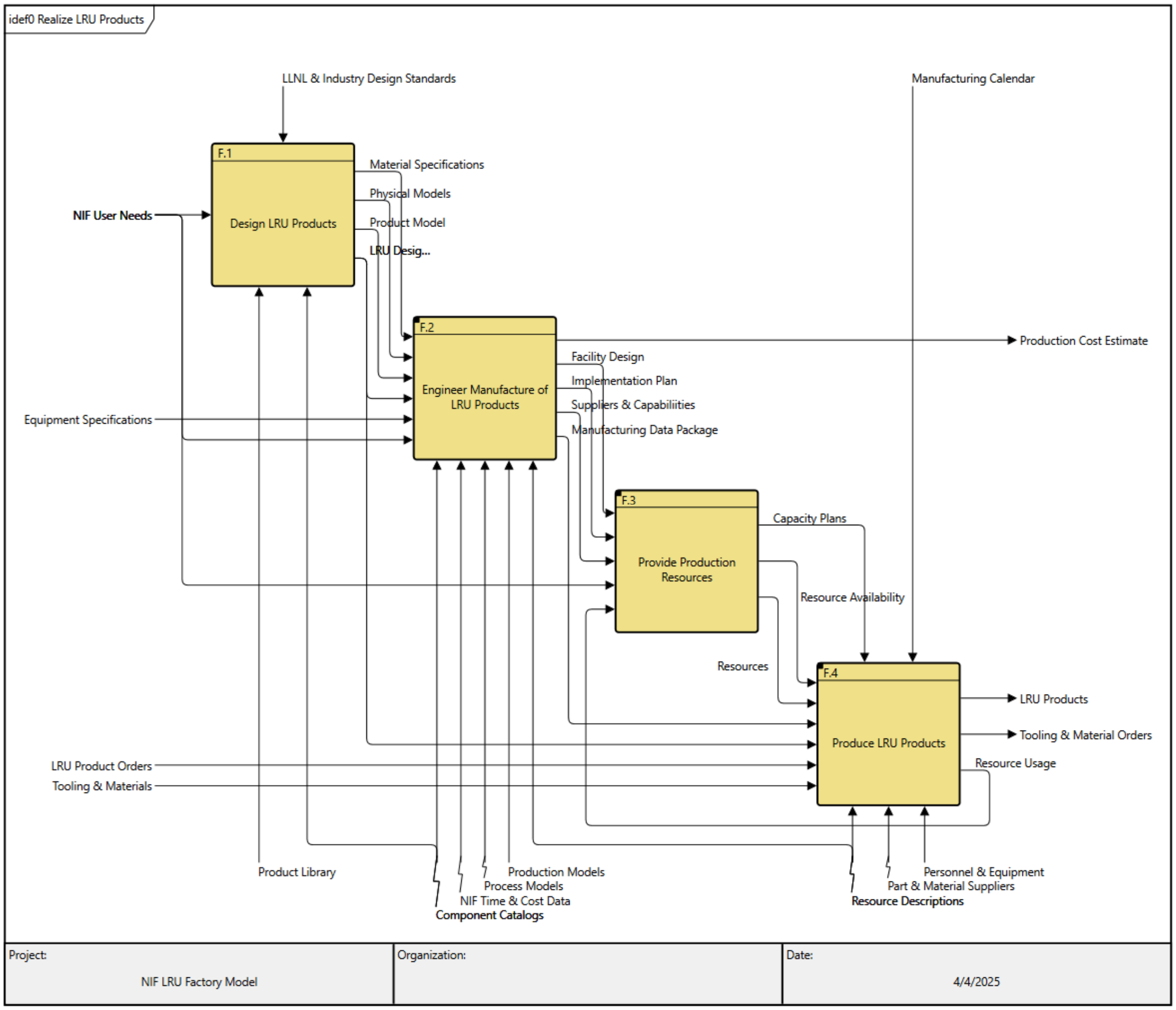

Figure 9: First Level Functional Decomposition of F.0 "Realize LRU Products"

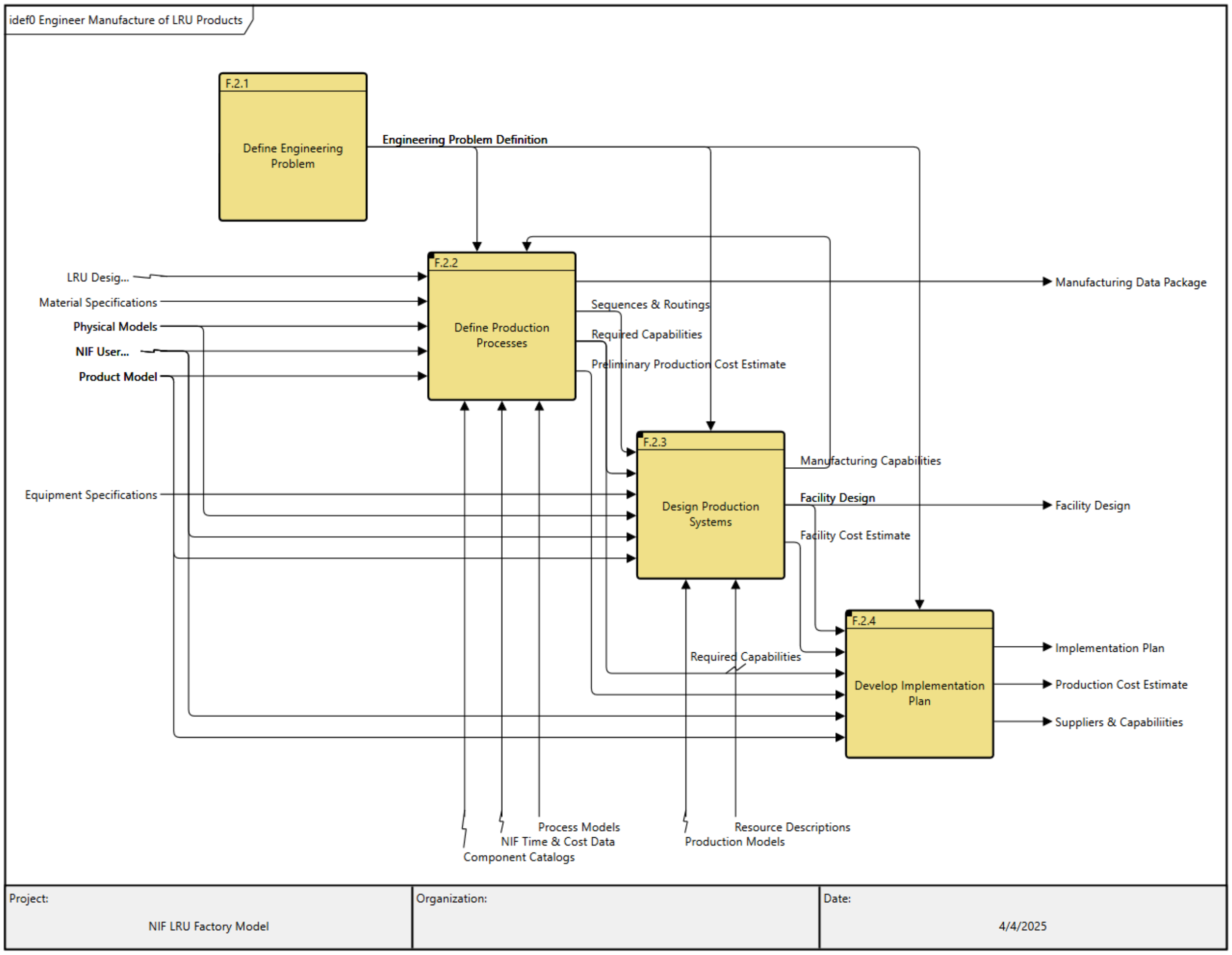

Figure 10: Second level functional decomposition of F.2 "Engineer Manufacture of LRU Products"

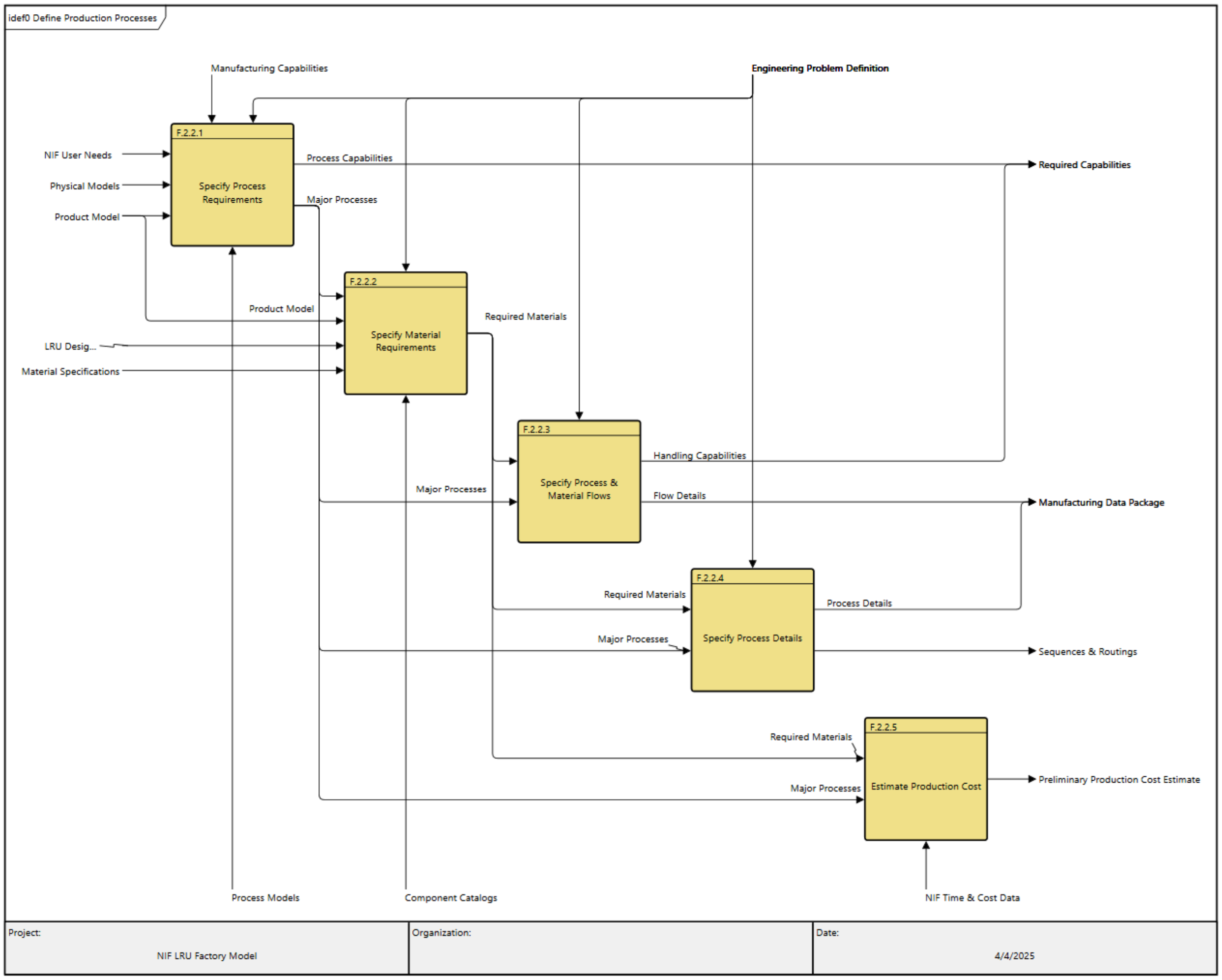

Figure 11: Third Level Functional Decomposition of F.2.2 "Define Production Processes"

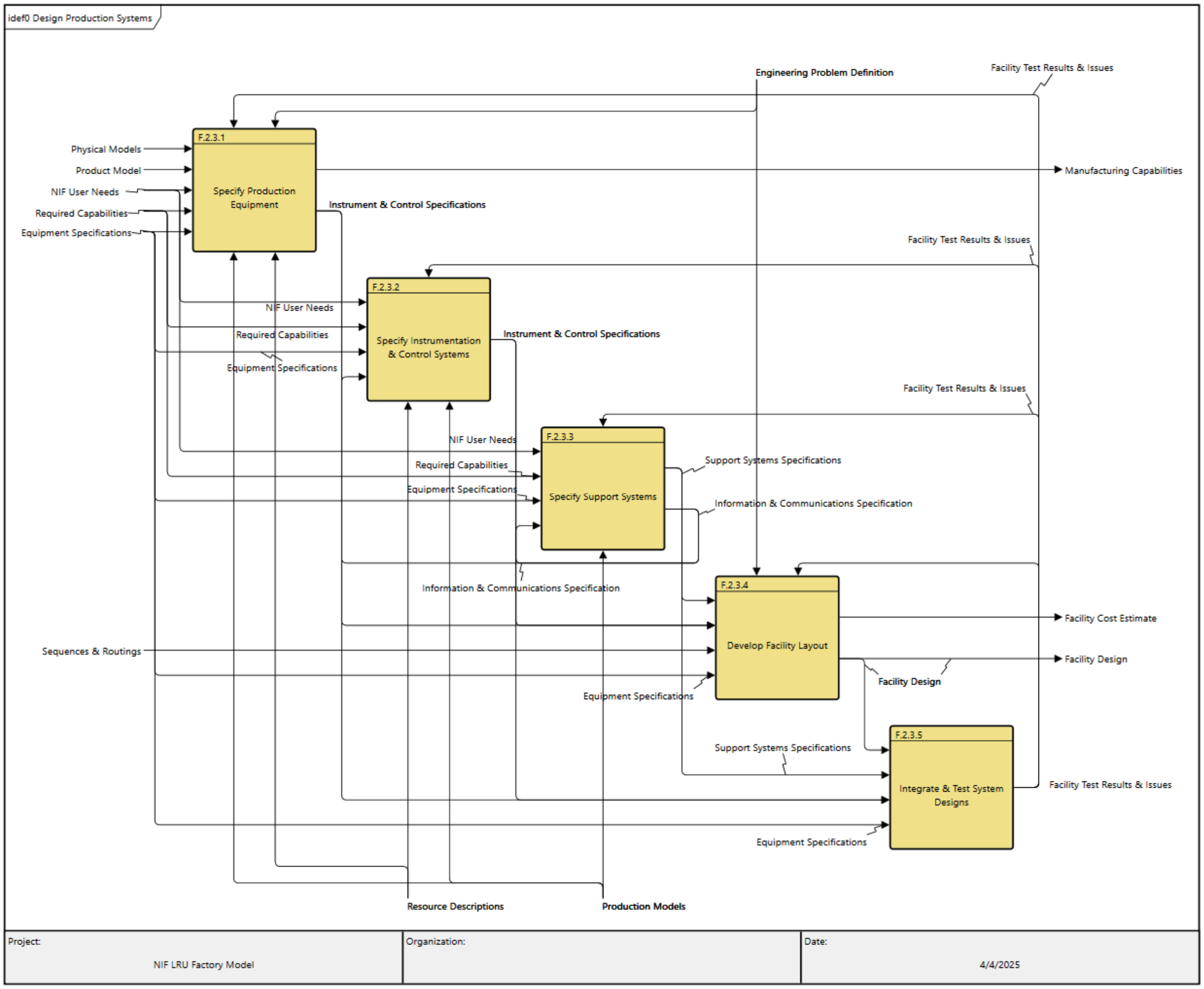

Figure 12: Third Level Functional Decomposition of F.2.3 " Design Production Systems"

F.2.4 "Develop Implemenation Plan"

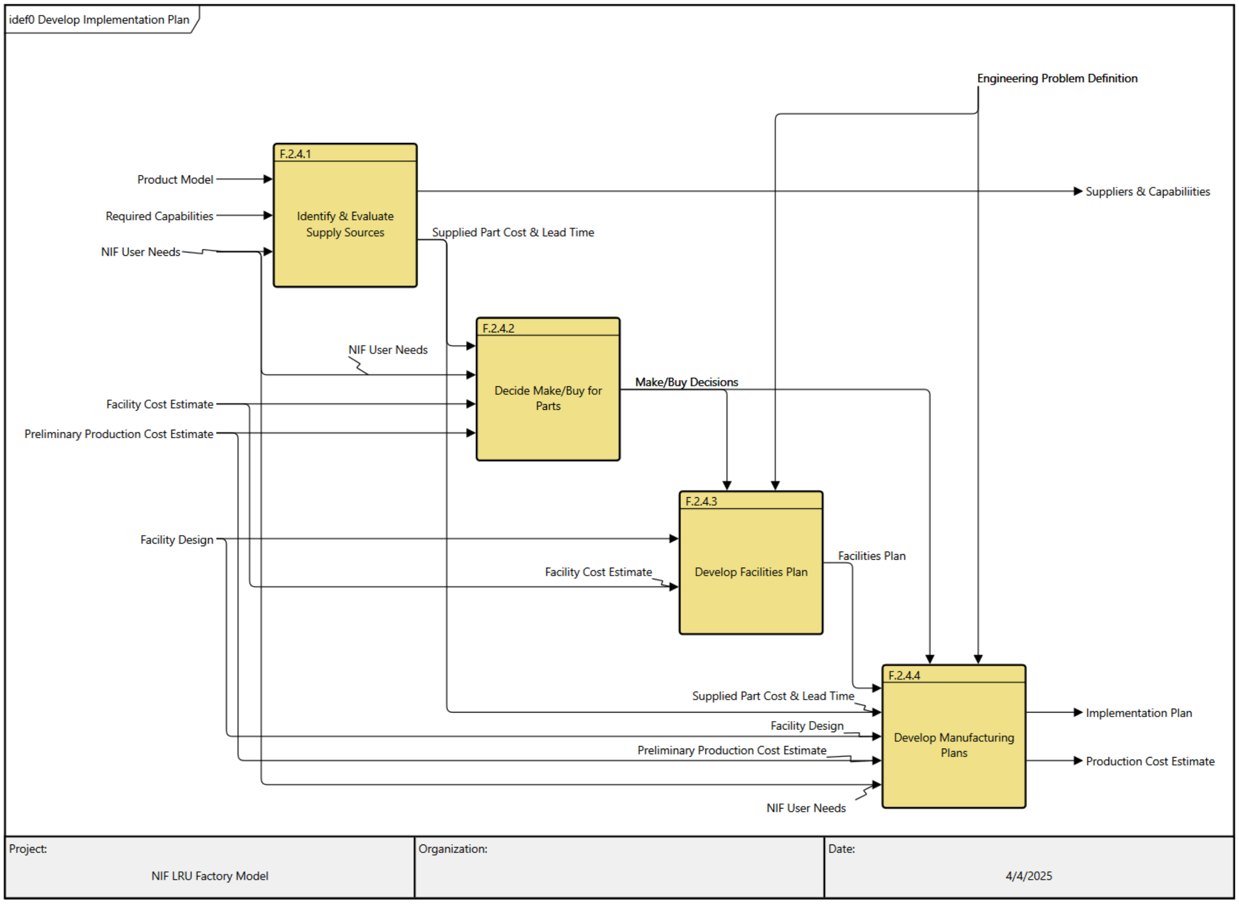

Figure 13: Third Level Functional Decomposition of F.2.4 "Develop Implemenation Plan"

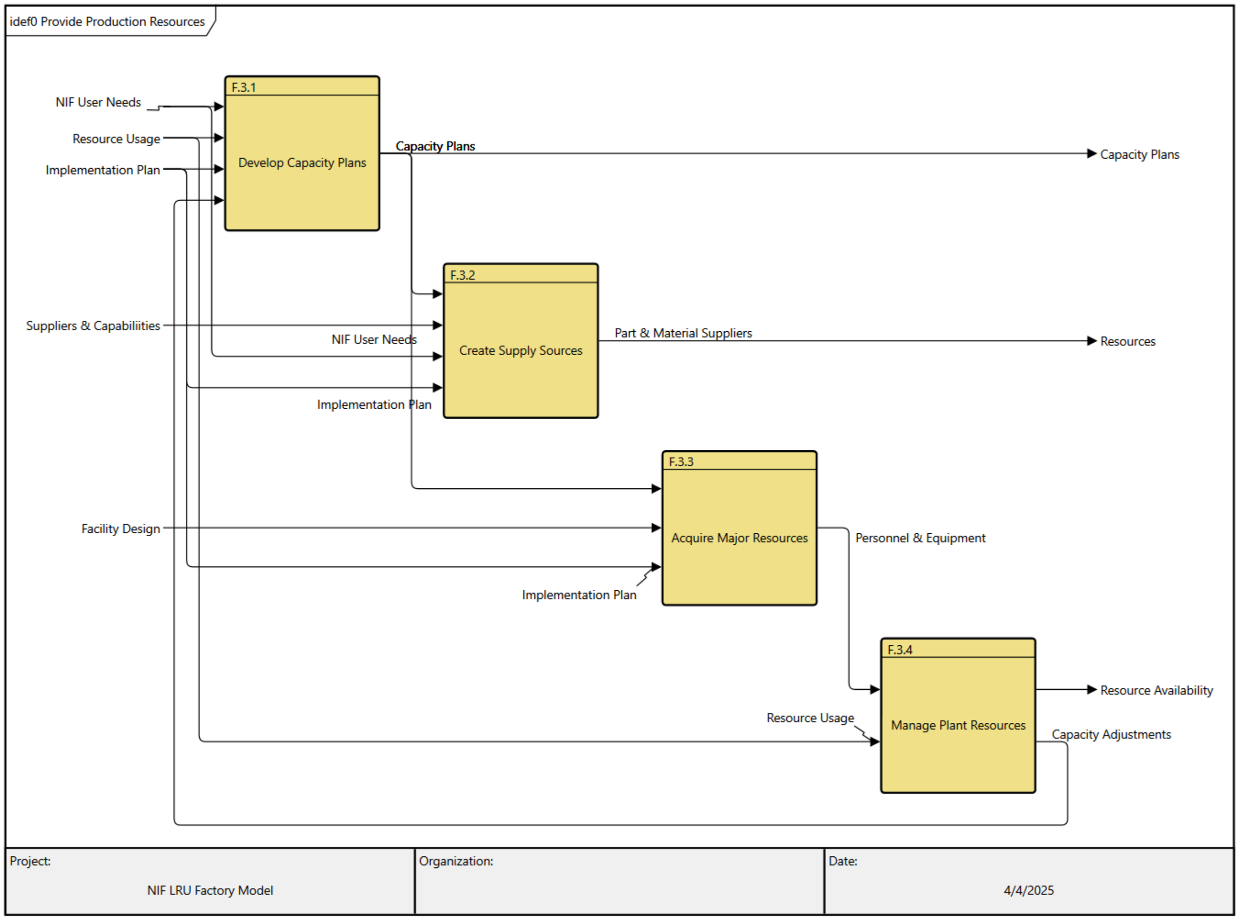

Figure 14: Second level functional decomposition of F.3 "Provide Production Resources"

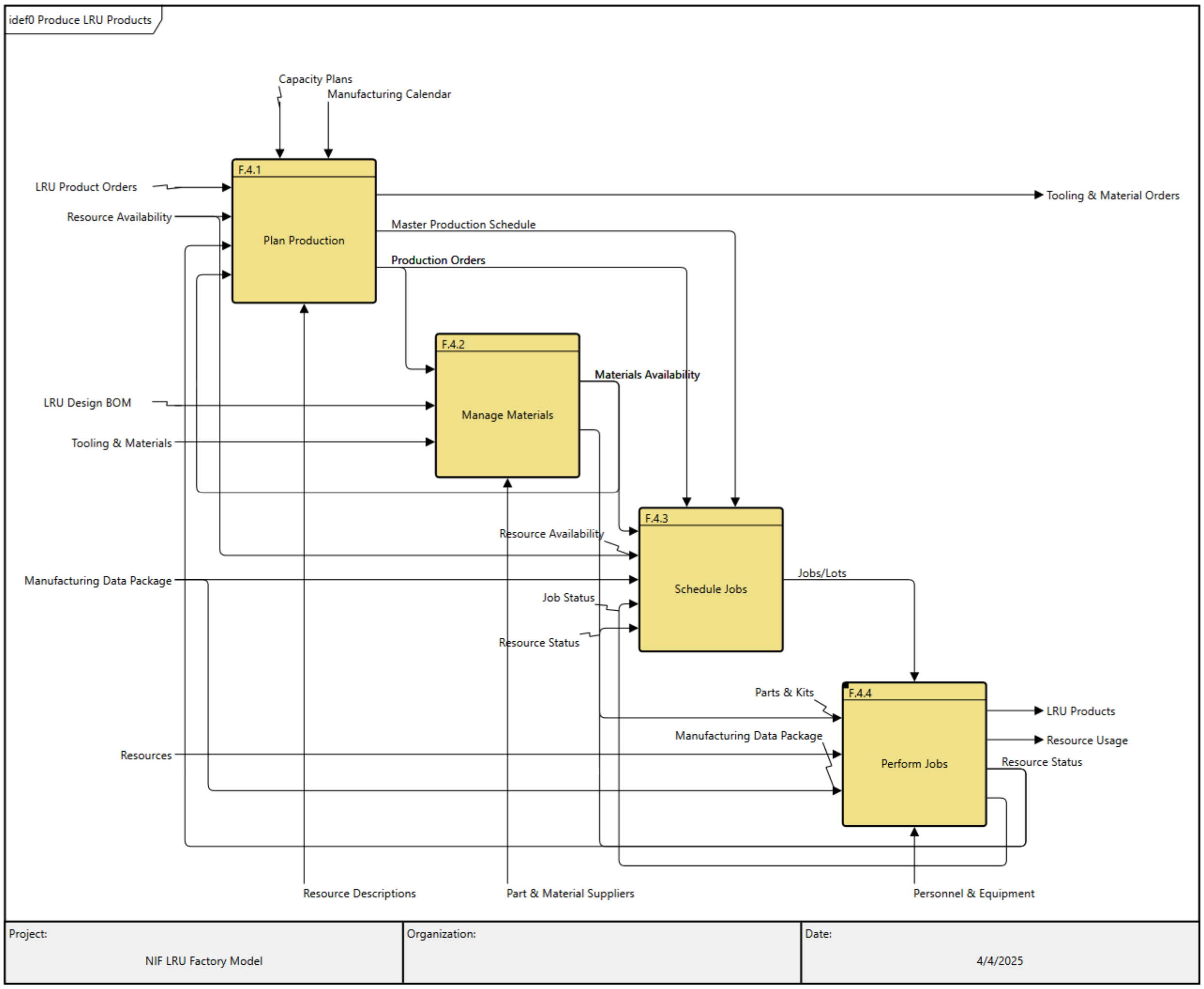

Figure 15: Second level functional decomposition of F.4 "Produce LRU Products"

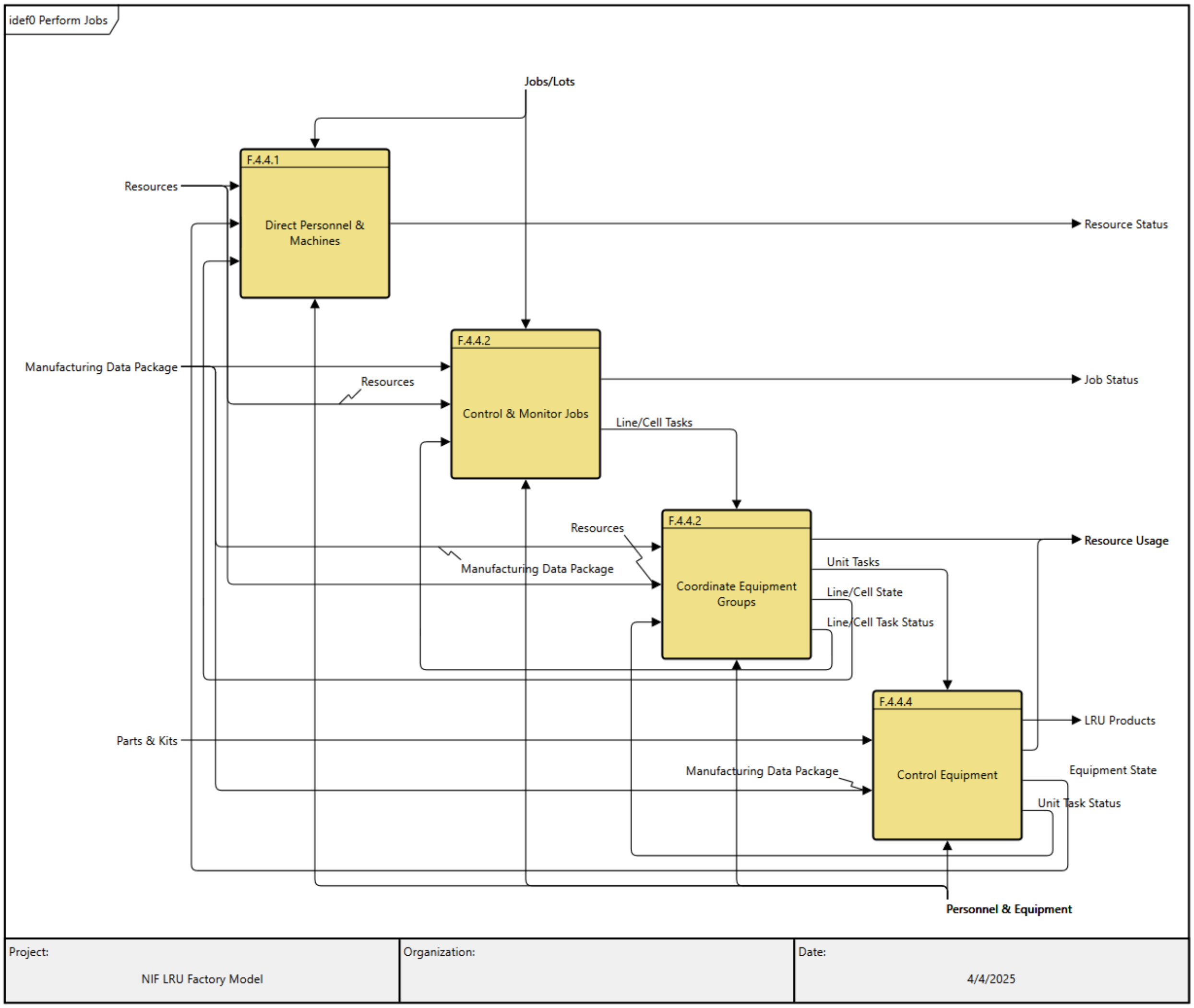

Figure 16: Third Level Functional Decomposition of F.4.4 "Perform Jobs"

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