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ABSTRACT

Astronomical observations of distant and faint X-ray sources will expand our understanding of the evolving universe. These challenging science goals require X-ray optical elements that are manufactured, measured, coated, aligned, assembled, and tested at scale. The Next Generation X-ray Optics (NGXO) group at NASA Goddard Space Flight Center is developing solutions to the challenges faced in planning, constructing, and integrating X-ray optics for future telescopes such as the *Lynx* Large Mission concept for the Astro2020 Decadal Survey on Astronomy and Astrophysics, Probe Mission concepts AXIS, TAP, and HEX-P, the Explorer Mission concepts STAR-X and FORCE and the sub-orbital mission OGRE. The lightweight mirror segments, efficiently manufactured from blocks of commercially available monocrystalline silicon, are coated, aligned, and fixed in modular form. This paper discusses our first attempt to encapsulate our technology experience and knowledge into a model to meet the challenge of engineering and production of the many modules required for a spaceflight mission. Through parallel lines of fabrication, assembly, and testing, as well as the use of existing high throughput industrial technologies, $\sim 10^4$ coated X-ray mirror segments can be integrated into $\sim 10^3$ modules adhering to a set budget and schedule that survive environmental testing and approach the diffraction limit.

Keywords: X-ray optics, optics manufacturing, optical assembly

1. INTRODUCTION

Studies of distant and faint X-ray sources offer exciting research areas for developing our understanding of the evolution of the universe. To achieve the ever demanding optical performance requirements to meet these science goals, the proposed X-ray telescopes of the coming decades require resolution that approaches the diffraction limit with a collecting area consisting of many nested reflecting surfaces[1,2] (see Figure 1).

1.1 Polished Silicon Optics Concept

The Next Generation X-ray Optics (NGXO) technology development group at NASA Goddard Space Flight Center is developing manufacturing processes to construct an X-ray mirror assembly to meet the ambitious science goals with an achievable and well characterized schedule and cost for fabrication, integration, and testing. The mirror technology under development is hierarchical in design, compatible with mass fabrication and testing in parallel operations.[2,3] Figure 2 shows the four levels of the modular meta-shell concept and the number of elements needed for the Large Mission X-ray telescope concept *Lynx*. This approach to constructing the *Lynx* mirror assembly can be scaled down for the smaller Probe and Explorer class missions.

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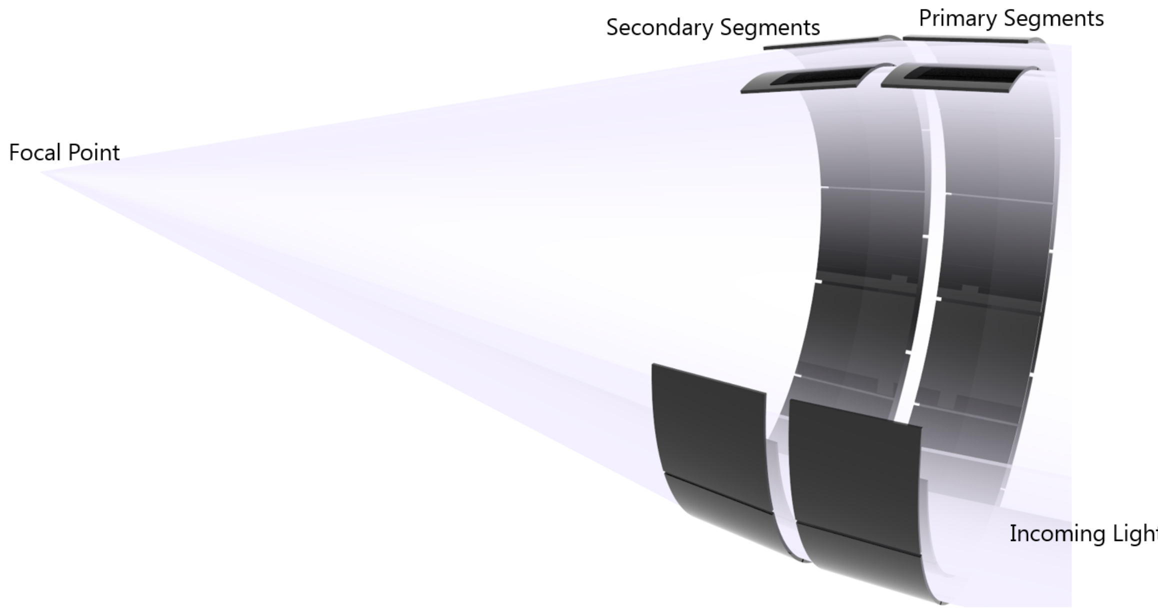

Figure 1. Many nested shells consisting of lightweight segments are one way to increase the photon collecting area of X-ray telescopes.

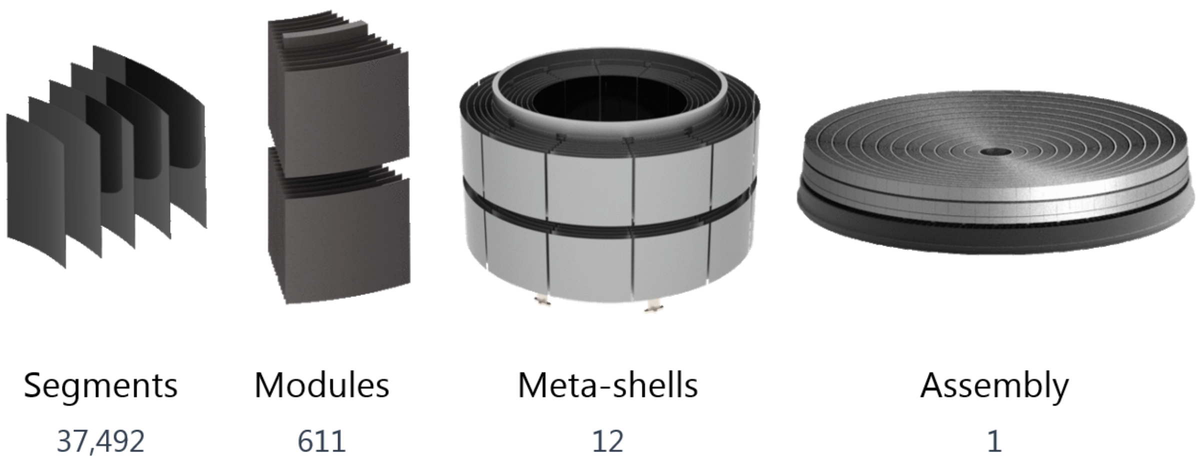

Figure 2. Technnology paradigm to construct future large collecting area X-ray mirror assemblies currently under investigation for the *Lynx* telescope concept, including the required number of each component.

1.2 Current State of Polished Silicon Optics Technology Development

Polished substrates that meet optical requirements and have well defined fabrication steps are currently being produced to support technology development at the segment coating and module level.[4,5] Figure 3 shows a high level view of the fabrication steps. Segment coating to increase X-ray reflectivity, including coating stress compensation approaching the quality requirement specified in the *Lynx* error budget, has been demonstrated in a laboratory environment.[6,7] Further work remains to demonstrate this segment coating and coating stress compensation approach in a production-like environment. Similarly, module integration development is currently focused on meeting science requirements at the single mirror pair level using full illumination X-ray performance tests,[8–10] yet multiple pair modules that pass all environment and performance tests at a production level remains to be demonstrated. Table 1 summarizes the significant fabrication steps required in each phase of production. Section 2 details the challenges and potential solutions to perform these steps for large missions. Despite the

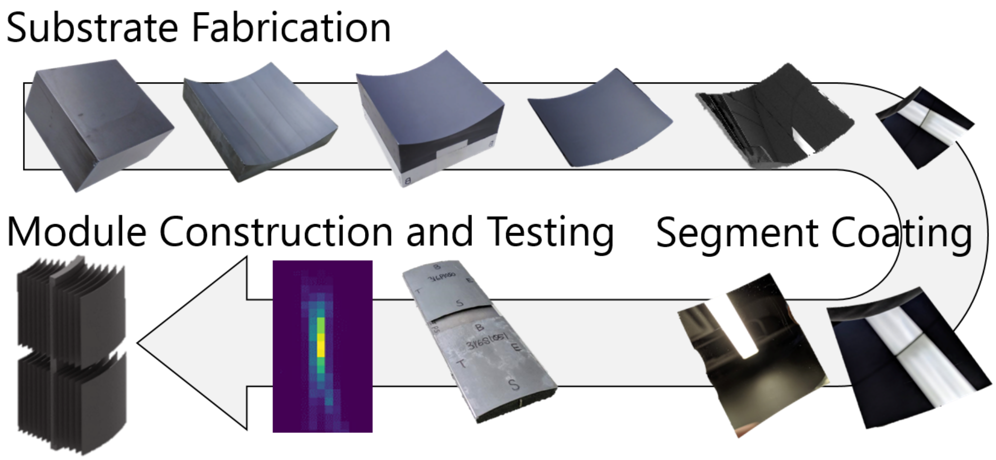

Figure 3. Overview of steps required to deliver mirror modules for further assembly.

current lack of well tested, production-ready fabrication steps, especially beyond the substrate fabrication phase, the major steps can be enumerated in sufficient detail for an early feasibility study to identify areas of potential risk when transitioning from technology development to production.

Table 1. Summary of current major steps required to assemble and test mirror modules in production, subject to improvement with further technology development.

Substrate Fabrication	Segment Coating	Module Construction	Module Testing
Block grinding	Cleaning	Spacer installation	Vibration qualification test
Block lapping	SiO_2 growth	Rough alignment adjustment	Thermal-vacuum cycling
Block slicing	Strip front SiO_2	Alignment measurement	X-ray qualification test
Pre-polish treatment	Front coating	Fine alignment adjustment	
Polishing	Annealing	Alignment measurement	
Smoothing	Metrology	Epoxy bonding	
Light-weighting	Backside IBF		
Trimming			
Etch			
Metrology			
Ion beam figuring (IBF)			

1.3 Mirror Assembly Production Challenges

While there has been a focus on developing "production-friendly" fabrication steps (low labor and machine cost, high yield and throughput), additional improvements are still possible with further investment and testing in the technology development phase. Determining the downstream effects of common production level issues such as machine availability, variation in step duration, and expensive Ground Support Equipment (GSE) is also required in the pre-production phase. Due to the large number of segments and modules, it is advantageous to establish more than one vendor contract to fabricate and assemble the necessary components into modules. This approach requires systems level analysis to establish scope of work for each vendor contract in such a way to avoid costly bottlenecks. For all of the reasons in this section and more, it is necessary to model the production of mirror assembly components well before the start of production to mitigate schedule and budgetary risk.

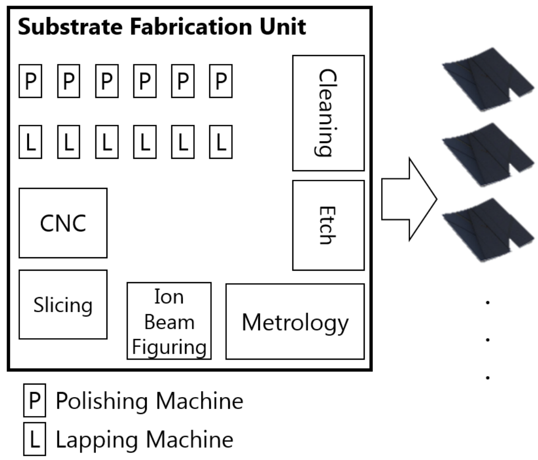

Figure 4. Graphical representation of one Production Unit (PU) designed for substrate fabrication.

1.4 Modeling Cost and Schedule

This paper will introduce one method to study the cost/schedule tradeoffs that occur when scaling production of qualified modules that continue on to be aligned and integrated into a larger mirror assembly. While it is possible to extend this model to other areas of mirror assembly construction, the large number of steps required to construct and test modules drive the bulk of the cost and schedule. In building such a model, it is necessary to keep track of capabilities that have already been demonstrated, technologies that exist in industry and can be adapted for use in large scale production, and capabilities that require further development and characterization before start of production.

1.5 Modeling Approach

Cost and schedule modeling of the *Lynx* mirror assembly production using queueing theory has been proposed.[11] In this approach, mirror substrates wait in a queue for one machine in a batch to become available to process the part before moving on to subsequent fabrication steps. A closed-form equation based on this approach for cost and schedule was derived. It is also possible to build a more advanced network of queues that more closely match characteristics of some fabrication steps (reworking a fraction of parts, reuse of metrology equipment, etc). This approach may yield an iteratively calculated cost and schedule.

The model developed for this paper relies on a software simulation of all parts as they are processed at each fabrication step. While there are drawbacks (no closed form solution and processing time), the software simulation allows for more fine-grained analysis. This cost/schedule software model is analogous to Finite Element Modeling (FEM) of more advanced geometries, boundary conditions, etc. compared to using closed-form mechanics of materials equations. The model used in this paper is classified as a Discrete Event Simulation (DES) and is constructed using the Python software package SimPy.[12]

1.6 Production Units

As part of the model definition and scaling the number of machines needed at each fabrication step, it is useful to introduce a concept called a Production Unit (PU). A PU is defined as a subset of fabrication or testing steps that occur in order, require similar facilities and labor, and contains the necessary hardware in quantities that minimize bottlenecks. Each PU can therefore be analyzed independently and the number and type of machines can be optimized. Scaling for various mission sizes requires defining each unit and how many of each unit type operates in parallel. Using this definition of a PU, four such unit types are defined for this paper: substrate fabrication, segment coating, module construction, and module testing. Figure 4 shows a visual representation of a PU analyzed in Section 3, including some of the machines necessary for substrate fabrication.

2. MASS PRODUCTION OF MIRROR MODULES

This section covers some of the ongoing work to develop an X-ray optic manufacturing approach that is amenable to mass production. In some areas, existing applicable technologies have been identified for future investigation and testing, some of which are included in the production simulation covered in Section 3.

2.1 Substrate Fabrication

Due to the larger number of steps required for substrate fabrication, and the amount of labor and time required for some steps, there is more to gain from improved throughput and unit cost compared to segment coating and module assembly. From the beginning of this polished silicon approach to substrate fabrication, each step was carefully considered in a future mass production environment.

Several steps, for instance substrate polishing, take place on easy to build and modify machines in an open loop process that requires little labor to operate. A majority of fabrication steps are performed by a single operator managing multiple machines at a time. The remaining steps that do require hands on treatment have seen dramatic improvements in part yield and a reduction in process duration. For example, our trimming process, thanks to recent improvements, requires overall less time and labor by significantly reducing damage left on the edge of the part as well as preparation time for the subsequent acid etching step to remove damaged areas of the silicon crystal structure. Another process improvement example is integrating our newly installed Ion Beam Figuring (IBF) machine into our metrology data pipeline to allow one operator to figure and measure multiple parts at a time. Despite the young age of substrate fabrication using polished silicon, our current set of machines and technicians can take commercially available blocks of silicon on Monday and deliver polished substrates by Friday that approach or exceed the quality of the best polished X-ray mirrors, currently in use on *Chandra*.[2,5]

To highlight current efforts at developing mass production versions of our fabrication steps, we are outfitting a commercial computer numerically controlled (CNC) machine to light-weight more than one segment at a time, which takes place with little operator oversight once the process is started. Additional parts are prepared in advance and machine downtime to swap in new parts is minimal. This type of process development requires little alteration of commercially available hardware and software.

Like previous and ongoing advancements in substrate fabrication, there are a wide range of existing technologies likely to be tested and implemented leading up to the start of production. Designs for custom machines (such as our lapping and polishing machines) will be formalized and machine builders will be selected to deliver turn-key assembled machines. All production machines will include barcode scanners for part tracking using a shared database that can be queried by managers. We will also investigate the need for automatic part loading for our CNC and IBF machines. Segments held in part holders can be installed into cartridges capable of queuing up to 50 parts with automatic part loading, barcode scanning and selection of surface profile removal data in the case of IBF machines. There also exists industrial lines that can be configured for substrate cleaning, etching and rinsing in batches with robotic loading to transfer from one step to the next. While preliminary research has turned up many such potential commercial solutions, further investigation is needed during the technology development phase to confirm compatibility with substrate fabrication.

2.2 Segment Coating

Like substrate fabrication, the segment coating steps are compatible with batch processing, thus reducing labor. This includes segment preparation, thermally growing SiO_2, frontside stripping of SiO_2, coating the reflecting surface with iridium, annealing of the coating, and performing stress compensation with selective removal of the SiO_2 layer on the backside. Besides a custom coating chamber with gate valves to reduce vacuum cycle time, the other machines are either commercially available or can be customized or adapted for use with the segment geometry.

2.3 Module Construction

While much work remains in reducing labor and increasing throughput for aligning and integrating segments into modules, the path forward for technology development is clear. The major steps that remain, mostly manual in the current form, can be further improved. For example, rough alignment of segments is a matter of using the mathematical telescope prescription along with affordable and easy to use thickness sensors to set the appropriate heights at the segment contact points via local material removal. This can be performed on segments without locking up resources such as the alignment light source and camera system used to optically measure segment alignment on a module stack. Once alignment measurement is performed for each segment, a fine alignment adjustment typically requires <1 micron of thickness reduction at specified contact points. This fine thickness adjustment is currently labor intensive compared to using an IBF machine. Applying and allowing epoxy to cure takes many hours for each segment. This segment bond process currently is performed in the alignment beam to allow for continuous monitoring. With additional testing, it may be possible to perform segment bonding outside of the alignment beam which will increase the degree of parallelism for this step in production. This possible future trade study as well as others may dramatically increase the module construction rate and reduce the overall costs.

2.4 Module Qualification Testing

Once modules are constructed, each will be subjected to environmental and X-ray performance qualification testing before further assembly into meta-shells. Future environmental testing and analysis will help set the pass/fail criteria for all modules to be tested under before continuing on to installation in an X-ray beamline for measurement of angular resolution. It is likely that environmental and possibly X-ray qualification testing will be performed in batches. A subset of modules ($\sim$10%) will undergo a full battery of environmental tests (thermal-vacuum, shock, random vibration, etc) in addition to more exhaustive X-ray characterization (off-axis response testing, performance at varying energies, varying orientations with respect to gravity, etc).

It is likely that dedicated beamlines will be needed to complete the module qualification testing in a reasonable amount of time. These beamlines will be designed specifically to accomodate modules, including a small volume separated with gate valves to reduce temperature recovery time after pump down, shared facilities at the source and detector ends to reduce facility footprint, and a suitable mechanical interface to support the modules during testing. The model in Section 3 is capable of estimating the cost and schedule for this necessary work during production.

3. PRODUCTION MODEL

In Section 2, applicable technologies that enable batch processing and unsupervised operation were discussed. The production simulation performed in this section is built to leverage those technologies that are deemed to have a high likelihood of successful integration into future production given several more years of technology development. Operating 24 hours per day, 7 days a week for many of the fabrication steps is reflected in the model definition.

3.1 Modeling Procedure

To begin, a comprehensive list of required steps to deliver assembled and tested modules is generated. Each step is characterized by the following properties:

- Costs
  - Fixed costs (independent of number of machines, e.g. GSE, raw materials, etc)
  - Machine cost (cost per machine, e.g. purchasing fees, installation, facilities requirements such as temperature/humidity control and clean room environment, etc)
  - Hourly costs (cost per machine per unit time, e.g. labor, maintenance, utilities, etc)

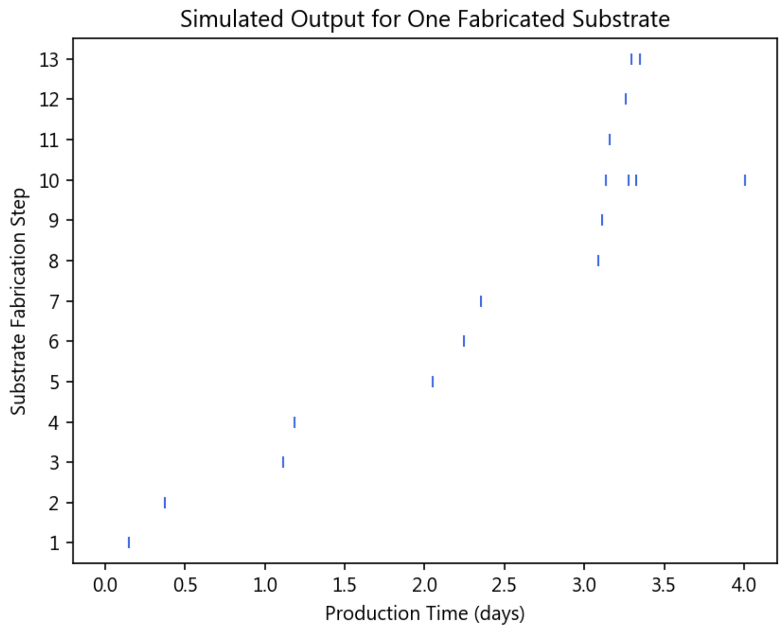

Figure 5. An example simulated timeline to fabricate a single substrate, including the possibility of reworking at some steps and operating on an 8 hour work schedule. Each tick mark represents completion time of a step.

- Performance
  - Batch size
  - Process duration
  - Variation in process duration (normally distributed)
  - Ship time to transfer part to the next step (with a normal distribution as well)
  - Required resources to perform the step (GSE e.g. lapping and polishing tools)
  - Yield (percentage of success)
  - Number of available machines
  - Chances of reworking a part
  - Machine availability (when not under maintenance)

There are several approaches to determine the number of machines needed at each step. In this example, using the proposed mission timeline, an appropriate delivery schedule of completed modules destined for further integration into an assembly is estimated. Each PU is then designed to meet the schedule requirements with the appropriate number of machines to meet the required throughput. Using the gathered cost information, each definition of a PU will have a resulting overall fixed cost as well as operational costs (cost per unit time).

3.2 Example: *Lynx* Substrate Production Units

After gathering all of the pertinent cost and performance information listed in the previous section, using conservative estimates where exact values are missing, 13 substrate fabrication steps were defined (from block grinding to polished segments ready for coating). The number of machines at each step were adjusted to remove bottlenecks in throughput (see Figure 6) and to complete all steps in a reasonable time span to deliver all substrates for segment coating. As a preferable alternative to increasing the number of machines, fabrication steps can be developed to be more efficient to remove bottlenecks.

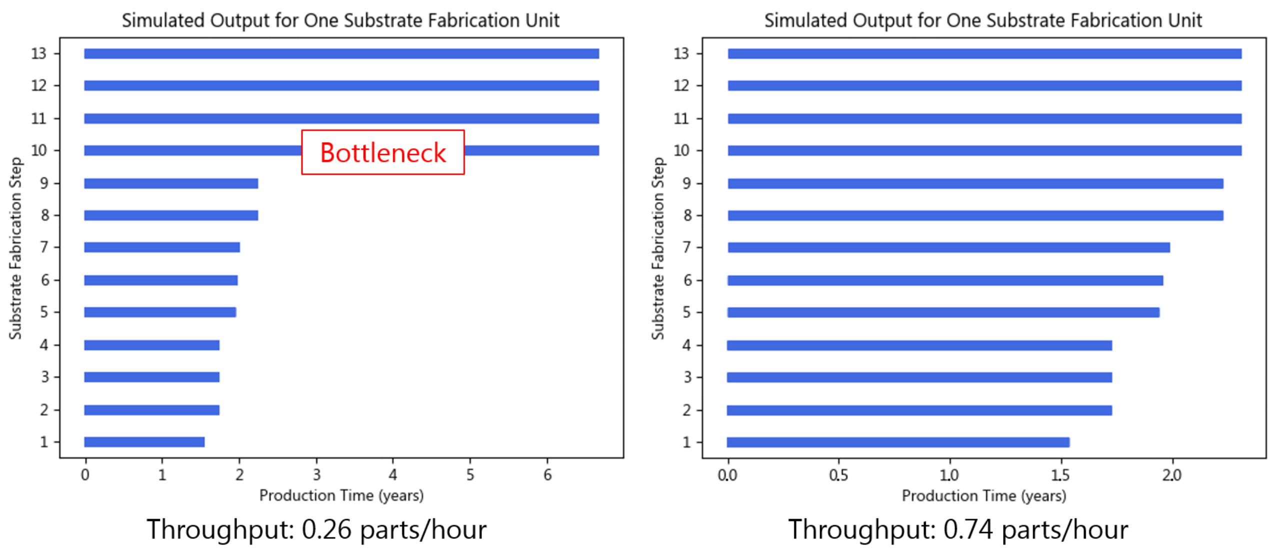

Figure 6. Simulated timeline of one *Lynx* substrate fabrication unit before and after adding machines to alleviate a bottleneck step along with the improved part throughput. Plotting many step completions using individual markers gives the appearance of a solid bar in the plots above.

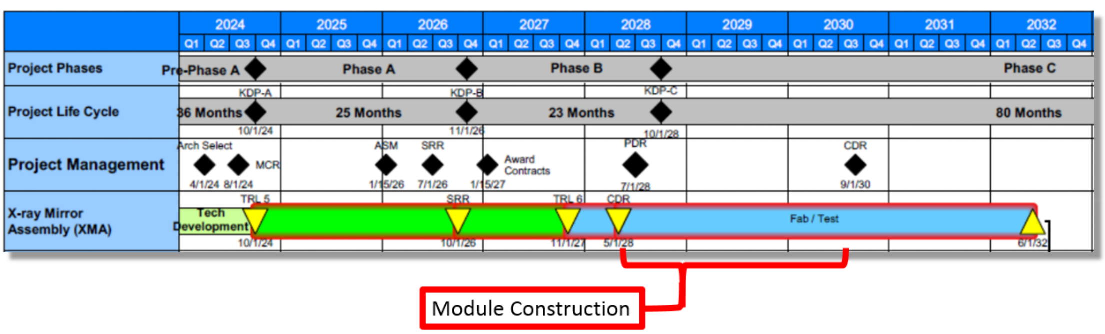

Figure 7. Proposed mission schedule for *Lynx*[13] including the approximate period of time in which module construction and testing take place.

The production of polished substrates ready for coating must take no longer than required based on the mission schedule. In the case of *Lynx*, substrate fabrication must take place in approximately two years to allow time for segment coating, module assembly, and module testing, see Figure 7. Bear in mind that meta-shell and mirror assembly construction will overlap with module construction. The duration limit or manufacturing span only defines when the final substrates are delivered for module construction. There may be flexibility in the ∼2 year manufacturing span which can require trade studies to analyze cost and other factors. Using the simulated throughput and costs of the defined PUs, such cost/schedule tradeoffs can be performed rapidly (see Figure 8).

3.3 Production Risks

Four categories of PUs were designed: substrate fabrication, segment coating, module assembly, and module testing. In each type of PU, steps that are cost or schedule drivers are identifiable. An example of a possible risk is the need for multiple cylindrical transmissive null lens metrology systems, which is currently the only non-commercially available or easy to construct component in the substrate fabrication step. Additionally, the cost of polishing and lapping tools comprise a significant portion of the substrate fabrication unit cost. Manufacturing and qualifying these tools may also need to be modeled into the schedule for future studies. During the technology development, alternative procedures that require less expensive or no tooling will be studied.

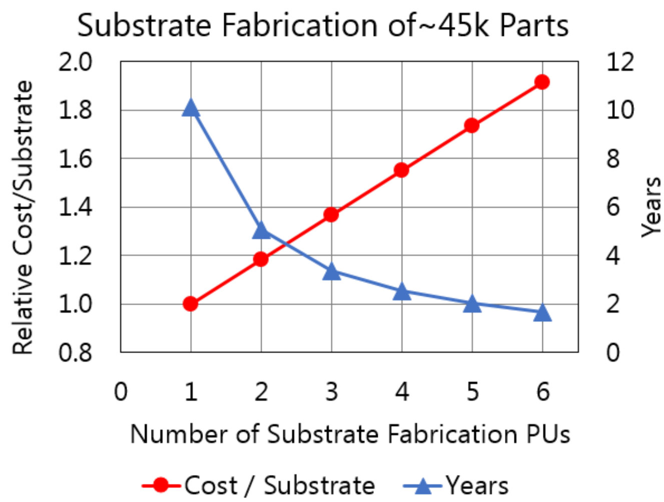

Figure 8. The cost / schedule balance of scaling the number of PUs of a specified design.

Module X-ray qualification testing may require more than one dedicated beamline to meet required throughput (see Section 2.4 for a description of the beamline). For modules that approach the diffraction limit, the source size (which drives the beam length) as well as the duration of the test are important cost and schedule drivers when designing such a facility.

Repeating this simulated module construction in the future as the fabrication and testing steps evolve will help focus short term efforts in reducing cost and schedule risk. Based on the significant process improvements that have taken place over the past several years, the process time, costs, and labor are expected to improve as manufacturing modules continues to mature.

3.4 Scaling for Mission Size

The simulated results for *Lynx* module construction and testing show that this approach is applicable for any sized X-ray mission concept. Over 1 million fabrication steps are simulated with each iteration of *Lynx* module production in minutes using conventional laptop hardware. It is possible to apply a tuning algorithm to optimize each unit in a matter of hours.

With new mission requirements, the division of fabrication steps into units and the number of each machine type will change. As these PUs are defined, it is important that the throughput in a chain of PUs is maintained so downstream PUs are not starved of parts. This is an important point to consider in production where one or more PUs are in fact contracted vendors that must deliver their parts to the next vendor in the chain.

4. CONCLUSION

Production models, like the model discussed here, are only as accurate as the statistics and captured details allow. In the absence of such data during early phases of technology development, conservative estimates can be substituted. An up to date understanding of each fabrication and testing step, including applicable industrial solutions, enable predictions of future capabilities during production. It is possible to further develop this modeling approach into a formal production error budget to aid establishment of delivery requirements for the entities involved (NASA, contracted vendors) in fabrication and testing X-ray optical assemblies for future missions.

Using the current state of the art in production of lightweight, polished, and coated silicon X-ray mirror segments integrated into modules, the cost and schedule to produce and test modules ready to be integrated into an assembly were simulated for the Large Mission X-ray telescope concept *Lynx*. The production model was shown to be capable of simulating real world manufacturing factors at each fabrication step including part yield, variation in process duration, occasional part reworking, expensive hardware, labor, operating costs and more for any sized mission. Some potential risks to cost and schedule were identified for further pre-production development. With reasonable assumptions and further investment in technology development, modules for X-ray mirror assemblies implementing directly polished silicon segments, can be mass-produced within a realistic time frame for various mission sizes.

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