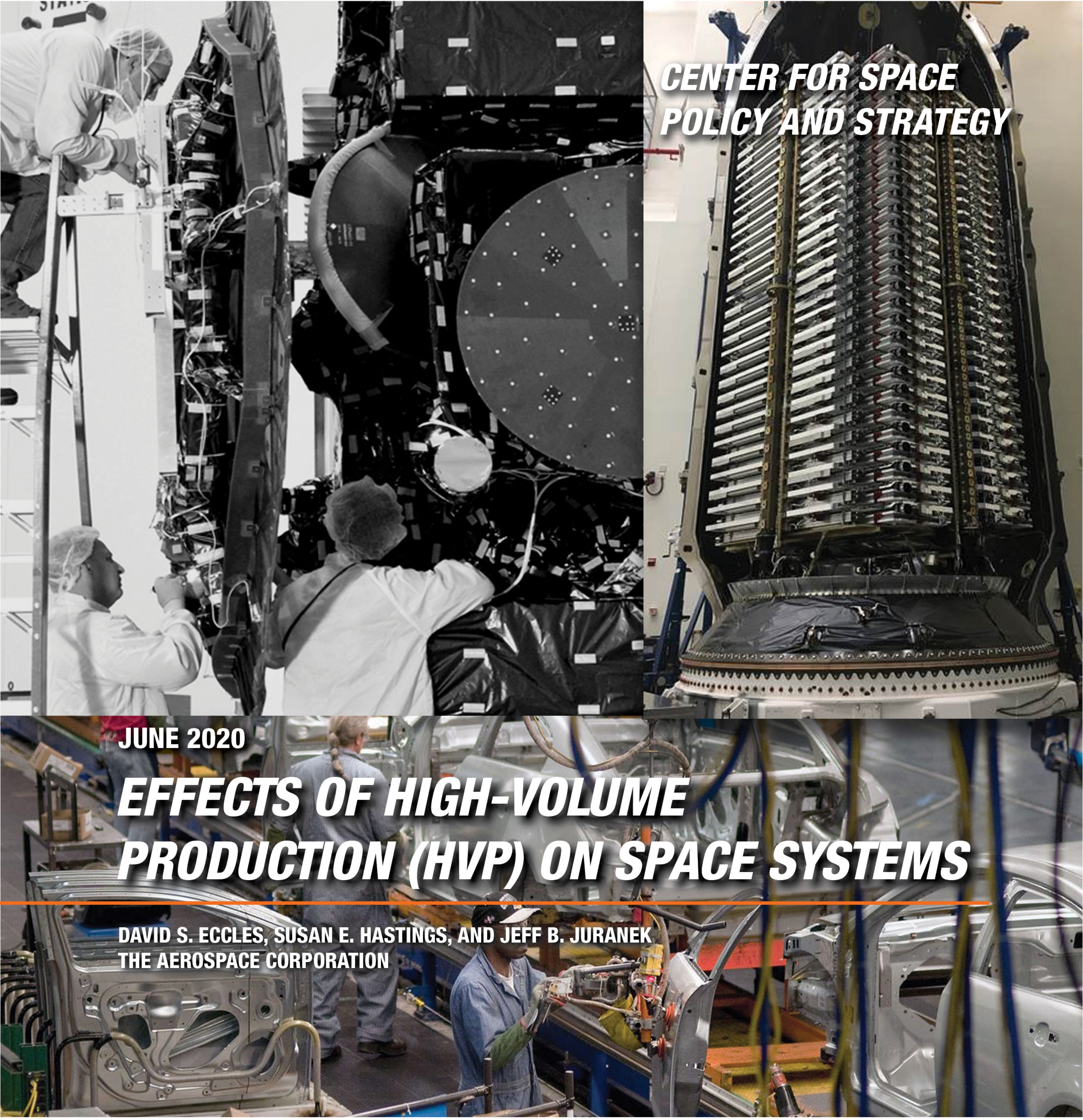

CENTER FOR SPACE POLICY AND STRATEGY

JUNE 2020

EFFECTS OF HIGH-VOLUME PRODUCTION (HVP) ON SPACE SYSTEMS

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Summary

The space business is undergoing a disruptive transformation. Capital has been poured into space enterprises, supporting both satellite and launch vehicle production in larger numbers than previously seen. A few companies have constructed manufacturing facilities to produce satellites at faster rates—potentially producing several per day. Comparison with other industries indicates that satellite production could benefit from methodologies employed for mass production of other complex systems (e.g., airplanes, automobiles, etc.) that must be reliable. This paper takes traditional production approaches and considers how they might be used to produce very large satellite constellations. It also discusses the effects that high-volume satellite production may have on national security space. We also outline a design for production (DFP) framework that captures principles, strategies, and techniques gleaned from other industries that we believe are applicable to satellite manufacture. Production principles and the DFP framework are described in the appendices.

Introduction

Much like the original horseless carriages or first aircraft at the dawn of the last century, designing and building satellites has mostly been a low-volume endeavor characterized by craft production methods. [1] Each satellite is essentially unique and built by hand, with the construction and verification taking months or even years to complete. A complex spacecraft like the James Webb Space Telescope is an extreme example, with construction to date at 11 years (and counting). Keeping manufacturing processes consistent is a challenge when building small numbers of hand-built satellites. Even so-called "clone" satellites, meant to replicate earlier versions, each have individually exclusive pedigrees reflecting workmanship variations, engineering changes to correct problems or increase capabilities, and required part changes due to obsolescence.

Several commercial companies are now planning, building, and deploying much larger numbers of spacecraft into constellations—a group of satellites that function together to perform a mission. Some of these will be large or mega constellations that number in the hundreds or even the thousands. Scaling up to such high volumes crosses a threshold that will require new methods and approaches.

Customer and user needs are changing, too. As the world becomes increasingly connected, users want to have the same communications and computing experience no matter where they are. Both governments and industry have a growing thirst for data that is best collected from space, and they have a matching need to transport that data rapidly from place to place to conduct military operations or do business. Because of their global coverage and low

Earth orbit (LEO) placement, companies that build mega-constellations hope to cash in on these desires. To do so, they are rethinking the production approaches used over the last 50 years.

Scaling Up

Traditional vs. Large Constellation Satellites

Until recently, most satellites were built either for a single use application or for use in relatively small groups. Even the Global Positioning System (GPS), a constellation of approximately 30 satellites that work together to help us find our way around (as well as helping the military precisely locate things), only requires construction and launch of a few satellites each year to maintain. In this paper, such satellites will be called *traditional* satellites.

These are in sharp contrast to constellations proposed by companies like SpaceX, Telesat LEO, and Amazon that are planned to have hundreds or even thousands of satellites. For our purposes, we will call these *large constellation* satellites. Prior to 2014, the one historical example of a mass-produced large constellation is Iridium, for which 98 communications satellites were built for its Block 1 constellation in the 1990s and, more recently, 81 satellites for Iridium NEXT.

Table 1 highlights some of the companies that have actual experience building 10 to 100 traditional satellites of a given type. [4] The satellite size, complexity, cost, and production time needed to produce each of these vary greatly depending on their mission and orbit. Even with their somewhat larger numbers, they can still be considered traditional due to the production methods used to build them.

Table 1: Constellation Satellites Produced

Constellation/ Program	Manufacturer	Quantity Produced
DSP Phase 3	TRW	10
GPS I	Rockwell	11
GPS II	Rockwell	10
GPS IIA	Rockwell	19
GPS IIR GPS IIR-M	Lockheed Martin	13 (Run 1) 8 (Run 2)
GPS IIF	Boeing	12
GPS IIIA	Lockheed Martin	10
Iridium Block I	Motorola	98
Iridium NEXT	Thales Alenia and NGIS	81
Globalstar Gen 1	Alenia Spazio/SSL	64 (Run 1) 8 (Run 2)
Globalstar Gen 2	Alcatel Alenia	24 (Run 1)
O3b	Thales Alenia Space	12
Flock 1 Flock 1b Flock 1d	Planet Labs	28 (Run 1) 28 (Run 2) 26 (Run 3)
Flock 2e Flock 2k	Planet Labs	20 (Run 1) 48 (Run 2)
Flock 3p Flock 3r	Planet Labs	88 (Run 1) 16 (Run 2)
Flock 4a	Planet Labs	20

Note 1: Production run = same design and continuous production time frame

Note 2: Quantity produced = constellation + spares + pathfinders + qualification models

In contrast, Table 2 lists some of the large constellations that have received Federal Communications Commission approval. Some of these have already started production using new methods, and Starlink had over 480 satellites on orbit as of June 2020. [5],[6],[7],[8],[9],[10],[11]

Table 2: Planned Large Constellation Satellites

Constellation/ Program	Manufacturer	Planned Quantity
OneWeb Satellites Gen 1	Airbus-OneWeb	648
Starlink V1.0	SpaceX	4,425
Telesat LEO	Airbus or Maxar/ Thales Alenia	117
LeoSat	Thales Alenia Space	108
Kuiper	Amazon	3,236
Kepler Communications	Kepler (in-house manufacturing with partners)	140

The production scale and capital investment changes as production increases from tens to hundreds to thousands of units. Satellites have never been produced in the thousands for a single constellation, and different methods and infrastructure for this ***high-volume production (HVP)*** are required.

For space, what constitutes HVP is debatable. Traditional satellites consider themselves "in production" as soon as they move past their first unit. This allows for a reduction in non-recurring engineering (NRE) on subsequent articles. [12] It follows that units "in production" are cheaper per unit and are completed faster with fewer flaws.

HVP is not a new idea. Automobiles have been mass-produced since the 1910s and 1920s. [1] Commercial airplanes, automobiles, and consumer electronics all use production approaches that yield insights that can be adapted for use in the manufacture of large constellations of satellites. Highly complex commercial HVP products are built efficiently, with high quality, and can be brought to market quickly. Table 3 highlights key differences between methods used to build traditional satellites versus large constellation satellites. [13] For an explanation of the fundamentals of various manufacturing systems, refer to Appendix A.

Naturally, customers expect their satellites to be launched on time, without flaws, and to work reliably throughout the entire mission life—all at an affordable cost. But designing and building satellites is unforgiving and complex. They must survive a violent launch process, then operate in an extremely harsh environment for years, with only limited ways to fix problems once they are deployed. These facts result in inherent functional complexities and interdependencies, with electrical, mechanical, structural, thermal, and material challenges that drive satellite design and manufacturing.

Regardless of constellation size, the rigor and attention to detail remains the same. However, designing and building satellites in *high volumes* introduces additional challenges. That's where the lessons of HVP from other industries can help.

Table 3: Comparison Between Satellite Production Methods

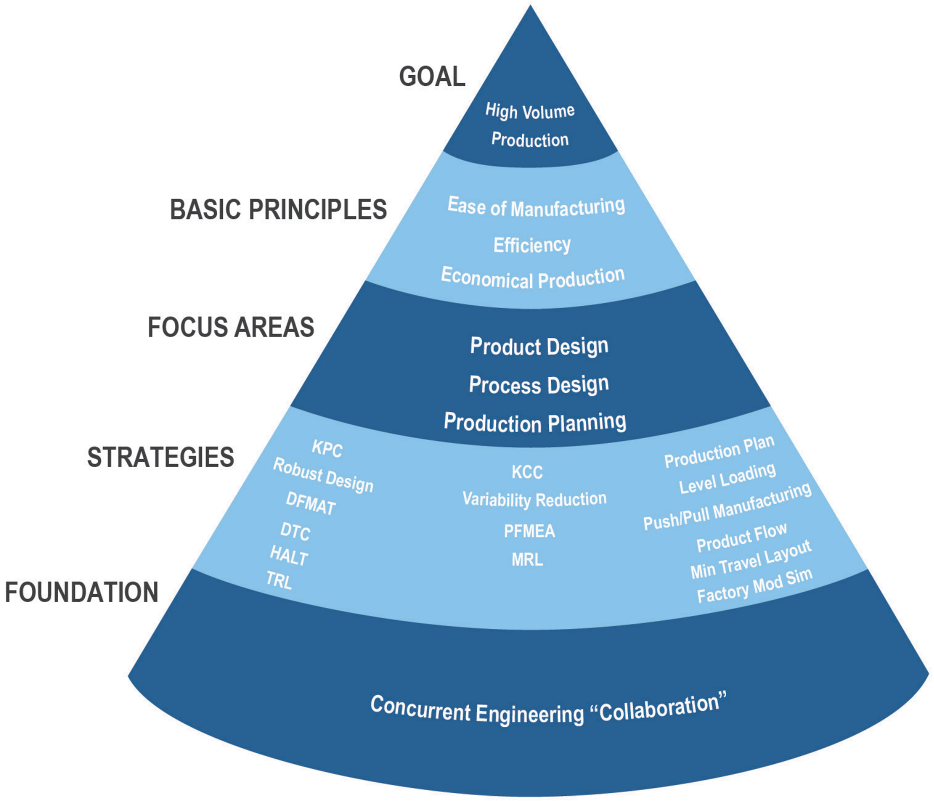
Traditional Satellites	Large Constellation Satellites
Low production volumes (≤100)	High production volumes (>100 to 1000s)
Built in multiple locations using project or batch processing	Built in one location using flow processing
Low process yields due to high rework/retest	High process yields due to virtually no rework/retest
Craft methods—resulting in lots of process waste	Lean methods—with little process waste
Production line stops often—typically waiting on part deliveries or anomaly resolution	Production line only stops in rare instances—no late hardware deliveries
Satellite sits for large amounts of time before a value-added operation occurs	Satellite moves steadily, and value-added operations occur consistently
First flight satellite tested using proto-qualification approach	Development satellites tested using a qualification approach and HALT (discussed below)
Manual testing and inspection verification	Automated testing and process validation
Build, inspect, rework, test—troubleshoot, retest, close paperwork—ship, re-verify, launch	Build, verify, ship, launch

Learning from Other Industries: Design for Production (DFP)

Design for production (DFP) for product design is the engineering practice of designing products that are easy to manufacture. The philosophy of DFP is to "design quality into the product, not inspect or test it in." Figure 1 represents the most applicable elements of production techniques and strategies from other industries for satellite production. At the top of this DFP framework is the goal of achieving HVP—in this case, to successfully produce and deploy a large or mega-constellation. The next layer holds basic principles that guide production strategy: ease of manufacturing, efficiency, and economical production. The third layer shows the technical efforts that must be undertaken to develop HVP: product design, process design, and production planning. Next come specific strategies that are particularly appropriate for satellite design and manufacture. The foundation of the DFP framework is concurrent engineering, or collaborative engineering. [14],[15],[16] From other industries, we learn that successful implementation of DFP requires careful integration of design, manufacturing, and supply chain working together to satisfy the basic principles of HVP.

Ease of manufacturing is figuring out how to produce an item that meets engineering and quality requirements in the simplest, easiest way possible. HVP product and process design should favor simplicity and standardization—reducing the number of parts, the levels of assembly, the number of operational steps, and the number of pieces of equipment or machinery required to produce the product.

Efficiency is about how work is performed with the goal to reduce or eliminate waste. **Lean** production concepts, used in many other industries, outline seven types of waste: (1) overproduction, (2) correction, (3) material movement, (4) inventory, (5) excess processing, (6) waiting, and (7) motion.



Strategies (Acronyms)
DFMAT – design for manufacturing, assembly, and test
DTC – design to cost
Factory Mod Sim – factory modeling and simulation
HALT – highly accelerated life testing
KCC – key product characteristics
KPC – key product characteristics
MRL – manufacturing readiness levels
PFMEA – process failure modes and effects analysis
TRL – technology readiness levels

Figure 1: Design for production framework.

Economical production results when design of a product is coupled with simple, efficient processes during its production. Wise production planning results in a factory and production flow that minimizes waste and improves efficiency.

There are a number of accepted strategies used in other industries that can be applied to producing space systems. DFP strategies are recognized to simplify, standardize, and improve repeatability using robust product designs and optimized manufacturing processes. Appendix B provides further explanation of what these are and how they are associated with product design, process design, and production planning.

As the foundation, **concurrent engineering** optimizes product and processes by using a collaborative or concurrent approach rather than a consecutive one. Key organizational functions work together "concurrently" instead of "serially." Integrated product development teams optimize designs for the product and its manufacture to avoid problems and reduce costs. Concurrent engineering can improve communication, accelerate decisionmaking, generate more ideas, and lead to smaller but more frequent design reviews, which are important milestones for any product design. Early coordination can also mature designs more quickly. [20] Vital for HVP, this enables the designers to understand the effects of their choices on downstream manufacturing, assembly, and test operations.

It is true that early involvement by the manufacturing function has sometimes been part of space system design in that the technicians who built systems painstakingly by hand were consulted as part of the design process. However, applying that same approach for HVP requires early involvement by many more players. Process and manufacturing engineers, factory designers, and efficiency experts who understand how to effectively achieve flow production must collaborate with the product designers from the beginning of the work.

Qualifying Design and Process

For HVP, qualifying both the design and the manufacturing process up front is critical, because design flaws and process bugs must be eliminated before mass-production begins. There should be no "learning curve" from one unit to the next on an assembly line.

Design qualification for objects in space has always required rigorous environmental testing used to stress the hardware in different test profiles for either qualification, proto-qualification, or acceptance levels. For example, when satellite hardware is tested to qualification and proto-qualification levels, it is tested *beyond expected levels* of stress for multiple iterations. Full qualification testing uses up a piece of hardware's entire planned design life, and it is therefore not flown. Meanwhile hardware tested at proto-qualification levels can be flown because only a small portion of the design life is consumed. The goal is to set the right level of acceptance testing sufficient to ensure the satellite will succeed in its mission without using up any of its design life. The environmental testing standard (TR-RS-2014-00016) contains the detailed approach for implementing environmental testing. [29]

Hardware can also be tested to failure, far above the hardware design limits. Highly accelerated life testing (HALT) is a useful strategy from the DFP that combines environmental and operational stresses to this end and accelerates qualification testing. [23] For HVP, information learned through HALT, qualification, and proto-qualification using prototypes (i.e., test articles) can be used to set appropriately reduced stress levels for acceptance testing in the factory. Some large constellation builders have even taken the additional step of flying prototype spacecraft and assessing their on-orbit performance before finalizing their designs. When the goal is to build many hundreds or thousands of satellites through mass production methods, the time saved using these strategies can really add up. Design verification/qualification is essential when planning for HVP. [29]

Process qualification/verification is applied to the *production system* (factory, production line, etc.) to ensure it is ready to start high-rate production. In the automotive world, automakers apply a risk management procedure known as *run-at-rate* to ensure that each of the suppliers delivering critical components can produce them at a production rate matching the flow in the final assembly plant. Run-at-rate process verification is performed prior to the start of accelerated production. If serious shortfalls are found in a supplier's process, key process characteristics are not met, or capacity plans are inadequate to support volume production, corrective measures are required. In-process control and measurements provide confidence in product manufacturing consistency. Automakers apply this same procedure internally as well, to verify that the production system at the final vehicle assembly plant meets run-at-rate criteria. [30] These criteria can also be applied to HPV for satellite manufacturing.

This concentration of engineering effort to do expansive upfront engineering, qualification testing, and full verification of the production system with its supporting supply chains demands upfront investment and time. HVP thus requires a funding profile that "front-loads" resources and schedule. If done right, the payoff comes at the end when large numbers of satellites can be produced quickly and efficiently.

National Security Space (NSS)

Now that commercial companies are beginning to implement HVP, does it make sense for National Security Space to leverage that? If the size of NSS constellations grows, HVP approaches may justify the necessary up-front investments in time and capital.

Traditional NSS satellite production is a mature industry, with tried and true mission assurance approaches that deliver exquisite, highly complex technology solutions for a multitude of applications. Traditional satellite manufacturing is labor intensive and susceptible to human error and variability. [28] To compensate, emphasis is placed on expensive and time-consuming methods that check, recheck, test, retest, verify, and reverify the hardware and software, especially for missions of national significance. The traditional, risk-adverse approach for one-of-a-kind, complex space systems requires high performance, which can also increase cost. The high cost and low production volume create prolonged quality assurance methods, which are applied throughout the entire lifecycle. Failures result in late phase design updates, which drive up costs. [28]

Additionally, the pre-acquisition phase for traditional NSS systems takes more than five years on average from initial study to contract award. For first-build satellites, it averages more than seven years from contract award to launch. Inventory cannot be purchased until it is needed by manufacturing, and long lead items cannot be ordered or planned for until after the contract has been awarded. Delivery lead time is long to account for contract turn-on, design activities, and procurement lead times. Follow-on satellites that are considered "production builds" or "clones" still take three years to complete through batch manufacturing using a verified design with stable requirements. [28]

These traditional approaches do not support principles like affordability and rapid delivery. The traditional process is viewed as unacceptably slow and unresponsive given the need to outpace growing threats and support mission operations. By starting to build smaller and less complex satellites using flow manufacturing, baseline Department of Defense (DOD) spacecraft could have standard interfaces for sensors and adjunct payloads that might be integrated in an assemble-to-order configuration. This is well suited for a standardized HVP approach. Initial prototypes could be fully qualified and designed for manufacturing, and assembled, tested, and operated in the intended environment to prove out the design.

Figure 2 illustrates the overlap of traditional satellite design and process qualification with HVP and indicates where the process design, production planning, and on-orbit design test fit into the traditional qualification flow. In the HVP environment, subcontractors and suppliers become strategic partners and utilize the prime contractor's manufacturing planning and control system. They may even move in-house to be more tightly integrated. Automation and repeatable assembly and test processes with active feedback loops ensure high-quality and synchronization of each process step. [28] The elements highlighted in the green region of Figure 2 are the up-front steps that require significant investment prior to initiation of the assembly line. If large constellations are NSS goals, HVP is likely worth the up-front investments.

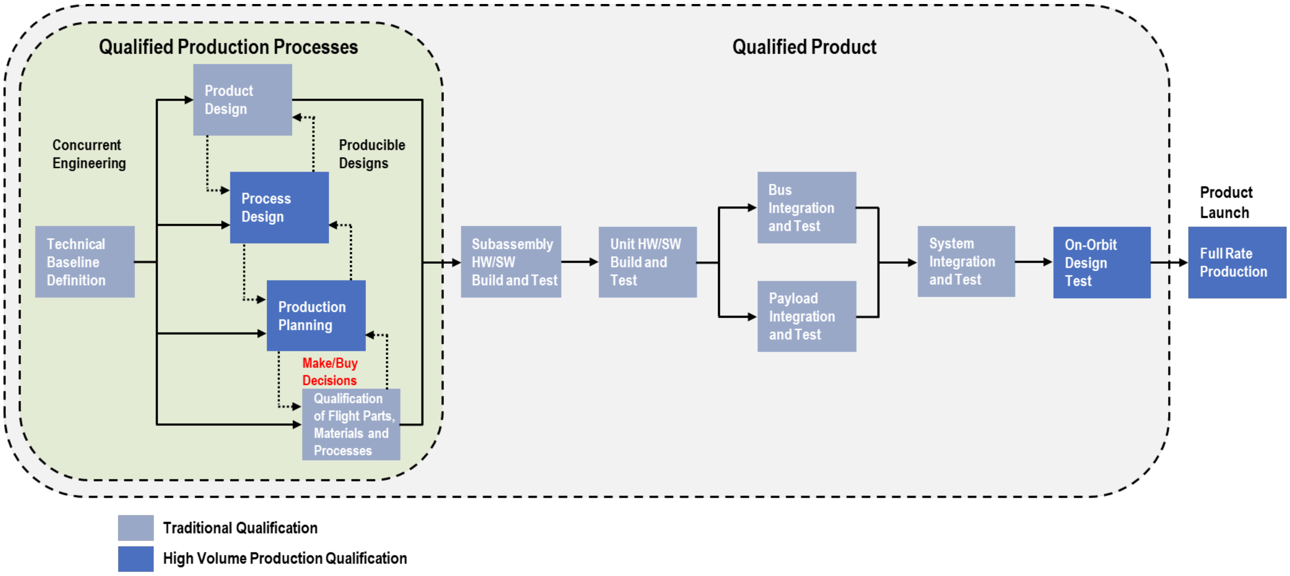


Figure 2: HVP augmentation to traditional qualification (mission assurance).

To hone in on the point of faster production/deployment times, Figure 3 compares the traditional satellite production timeline with an HVP timeline. In traditional satellite production, the ability to impact mission assurance endures all the way to launch. HVP moves this to the left, completing the qualification depicted in Figure 3 before the start of full-rate production. For HVP, mission assurance focuses on production and process qualification, eliminating time-consuming in-process inspection points and acceptance testing during full-rate production. Figure 3 shows traditional production being five years on average, but new HVP qualified designs could enter production every 2 to 3 years to meet user needs. [31] Using the existing Iridium Block I and Iridium NEXT as examples, new space entrants are focusing mission assurance efforts on the design and manufacturing qualification phases, looking to increase speed and efficiency in the manufacturing and test flow. The tenets of manufacturability and producibility are being applied as product lines mature to improve the time and cost effectiveness of manufacturing. Sources of waste are identified and minimized by error-proofing the design, arranging manufacturing in a flow, and collocating all required tools, supplies, and parts in the work area. Investments in technology can improve the speed, consistency, and accuracy of processes. Similar efforts are focused on the supply chain before manufacturing begins, which is the period when mission assurance must be focused to assure mission success. Although it's true that when building hundreds or thousands of satellites, it is no longer essential that every one of them work perfectly; it is essential that they not suffer from any common flaws that could have been detected and designed out.

Under HVP, when the design is complete and qualified, the customer and manufacturer "freeze" a design baseline, which will be captured in the digital engineering environment at the factory. The manufacturing line will then use data analytics to evaluate in-process measurements and monitor status. The manufacturer can make additional capital investments to streamline operations and reduce satellite manufacturing time, but only if there is a clear return on investment. Oversight by the government could be accomplished with a team that periodically reviews the adequacy of design and process improvements, with consultation from subject matter experts who maintain currency on the

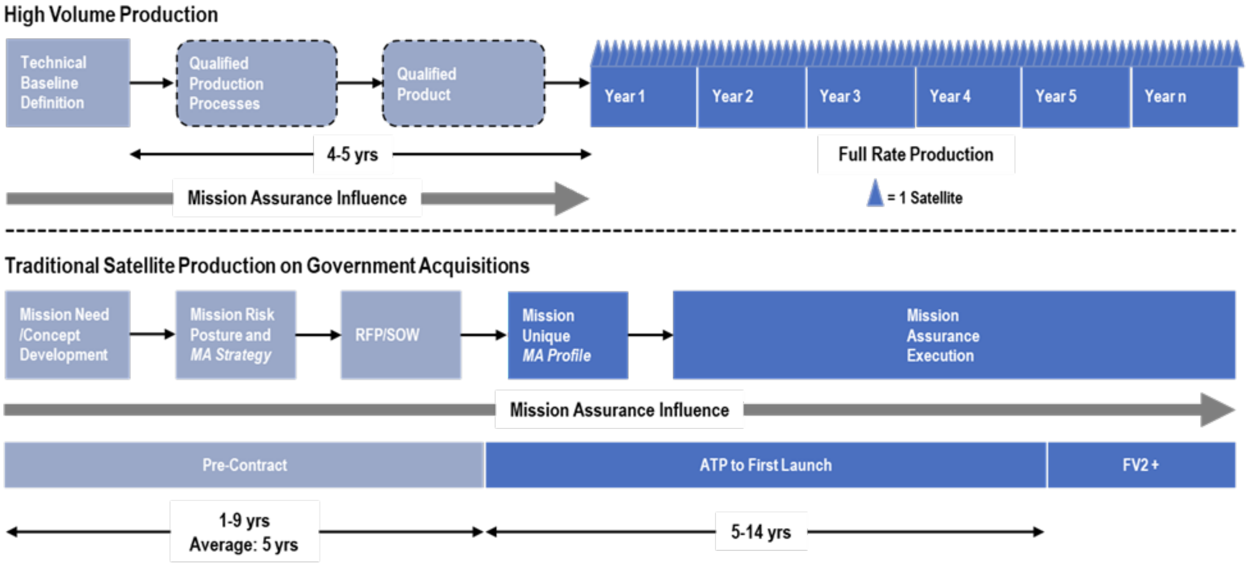


Figure 3: Mission assurance influence for traditional and HVP acquisition.

state of the assembly line. The quality associated with the satellite manufacturing line and individual satellite variants could be verified according to specific agreed-to standards. This approach allows the customer to monitor production effectively, while the manufacturer takes full advantage of improvements without suffering delays.

If the current crop of commercial mega-constellations becomes profitable, the government could experience something similar to the microelectronics industry disruption of the mid-1990s. The DOD dominated the customer base until the mid-1980s, levying stringent requirements for performance and reliability testing to predict failure mechanisms and lifetime. Then explosive demand in the lucrative commercial market coupled with a decrease in DOD purchasing resulted in reduced commercial interest in government customers. This forced the DOD to re-imagine its engagement with the increasingly global semiconductor industry. But the financial viability of the new HVP mega-constellations is uncertain. Although aided by the COVID-19 pandemic, OneWeb's recent filing for Chapter 11 bankruptcy protection is a case in point. Builders have yet to achieve a level of revenue that can sustain long-term operations and maintenance. Indeed, there are indications that some of the vendors desire U.S. government contracts to provide reliable revenue.

Future NSS programs may also be able to leverage commercially available HVP or partner with HVP providers to establish dedicated production lines. Space system HVP companies are starting to implement smart manufacturing technologies, including collaborative robots, smart tools, augmented reality, and automated testing with data analytics. These eliminate waste or can requalify processes during capital equipment upgrades that could save the government money in the long term. [22]

Space Acquisition: More Like the Rest of DOD?

Using HVP for NSS programs will put them more in line with DOD acquisition programs for aircraft and ground vehicles in terms of production rates, qualification testing, funding, contracting, and program office support. Typically, non-space DOD acquisitions have an initial low-rate prototyping phase that leads to later high-rate production. The funding profile for an HVP space system would also shift to a pattern more like those of non-space programs. After the big, up-front expenditures, actual production unit costs stay fairly constant and could even decline as production issues are resolved. Likewise, with contracting, which has early design and process qualification work under cost-plus and the HVP phase under firm-fixed-price contracts. This saves the taxpayer money. Another aspect seen in DOD acquisition for aircraft and ground vehicles is that program offices are largest during the development and testing phases, then shrink once the system enters HVP, freeing up the engineers to work on next generation follow-ons or new systems. This same pattern may manifest for HVP space programs.

Conclusions

Traditional project or batch manufacturing methods still dominate satellite production, but many organizations are evaluating HVP and some have implemented it. Builders and buyers are waiting to see whether large-scale manufacture of commercial satellites will be profitable. If so, HVP use will likely increase across the space enterprise. For NSS, the key will be a determination that large constellations are needed to improve performance and outpace the threat. If applied to NSS programs, HVP is likely to make them more like DOD acquisition programs for aircraft or ground vehicles in terms of funding, contracting, and program office size.

Continuous Production Agility

In March 2018, the Deputy Secretary of Defense asked The Aerospace Corporation to recommend an approach for building a more resilient space architecture capable of outpacing the emerging threat. Aerospace undertook a large study, from which came *Continuous Production Agility (CPA),* a concept that realigns space acquisition for speed, adaptability, and resilience through higher volume production, streamlined acquisition, and enhanced competition.

CPA focuses on delivering an entire constellation over a short period (e.g., five years) then immediately beginning the replenishment process on a schedule-certain basis. CPA's high quantity and high production rate strategy drives a predictable manufacturing cadence and incentivizes industry to invest for efficiency and speed. Increased satellite production diminishes dependence on individual satellite reliability. The intent is to support constellations that are more robust against threats and single-point failures. Shorter design lives enable simpler designs with less redundancy, reducing per-unit costs and partially offsetting the increased costs from production and launch quantities. Should HVP lines for satellite buses become available at some point, they might enable the CPA concept by offering affordable, reliable, and readily available satellite elements.

CPA adopts modular methods to establish production quickly and then increase or change capabilities cost effectively, as demand requires. For example, the U.S. government might contract with multiple providers for satellite buses or payloads, in support of multiple programs. To encourage innovation, competition, and schedule confidence, multiple parallel contracts could be established for the same capability, with each delivering a portion of the needed units. The CPA concept allows major components to be competed throughout the program's life, giving the industrial base multiple opportunities to participate. A key first step is development of modular bus/payload interface standards to shape future acquisitions.

Aerospace's CPA concept could be used to streamline space acquisition for greater speed, rapid technology refresh, adaptability, and resilience—including higher production rates.

To build very large satellite constellations in the future, HVP will be required. Such constellations will be built using flow manufacturing, and the overall product strategy will need to address ease of manufacture, efficiency, and economical production to meet cost targets and scheduled launch dates. HVP will change how risk is managed and mission success assured. Mission assurance activities will "shift to the left," concentrating in the early phases of development during design and testing, especially in setting up and qualifying the supply chains and designing the manufacturing systems. This requires significant up-front investment to ensure successful mass-production.

New methods adapted from commercial electronics, aircraft, and automotive industries can be applied to transform satellite design and manufacturing by placing an emphasis on simplicity, standardization, and more producible designs, as well as controlled, repeatable, and automated processes. If NSS adopts the principles of Continuous Production Agility (CPA) and/or moves to more proliferated architectures, HVP could help transform the national space enterprise with new HVP-qualified designs entering production on a timeline to outpace threats.

Appendix A: Production Fundamentals

A manufacturing system is a method of organizing production. There are three types of manufacturing systems: **project** manufacturing, **batch** manufacturing, and **flow** manufacturing. [2] The type used to build a product is highly dependent on the production volume, as well as the product movement and physical layout. Project and batch manufacturing utilize a **process**-oriented layout, while flow manufacturing is characterized by a **product**-oriented layout. Project and/or batch manufacturing results in low volume production, while flow manufacturing is used for HVP.

Project manufacturing is characterized by the production of one or a small number of high-cost, highly complex unit(s). Submarines, ships, and satellites are examples of project manufacturing. Once the major assemblies or subsystems are produced they are integrated in one or more locations. Throughput time can be months to years, characterized by a high degree of touch labor, rework and independent verification to ensure that the product meets requirements. [2]

Batch manufacturing is characterized by some variations in products, process requirements, and order quantities. An example of a batch-produced product is machined assemblies (e.g., machined piece parts). For batch products, the flow of work is variable and depends on the design of a product. With a variable work flow, the amount of time at each work center varies depending on the product design, and results in an unbalanced work flow. Machinery and equipment are arranged according to the function they perform (e.g., lathes, milling machines, etc.). Throughput time varies depending on the work content at each work center and can result in an accumulation of work-in-process (WIP) inventory depending on the capacity of the factory and the mix of products being built. Several satellite manufacturers are using batch techniques to build handfuls of satellites that each vary slightly. [2]

Flow manufacturing is for the HVP of standardized products. Flow manufacturing products are typically discrete units that are repetitively produced as individual units (e.g., aircraft, automobiles, etc.). Each unit is the same and is delivered with no differentiation between the units manufactured. Flow manufactured products generally have fixed routings and the work content at each work center is synchronized, creating a balanced flow. The product flows between workstations with little WIP inventory. Throughput time is short, and the capacity of the production line is fixed by the resources and equipment dedicated to that product. [2] This is the approach we have observed being used by OneWeb Satellites to support large constellation production.

Key Considerations for Manufacturing System Design

Choices about the manufacturing system design result from its **product strategy**, as tradeoffs are made between each of the inputs (Figure A-1). These inputs should be carefully chosen to support the product strategy and maintain alignment with the overall corporate business strategy. Key manufacturing system considerations are a function of three important focus areas for production: product design, process design, and production planning.

Production volume is the maximum volume that can be produced over a span of time and determines the factory capacity, while market demand determines the *actual* factory production volume. Selecting a maximum production volume determines the factory's physical design. It affects the floorspace needed, machine layout and selection, number and type of workers, number of shifts, and drives unit cost and factory operating cost. [2],[3]

Product mix refers to the number of different products that can be manufactured. If it is important

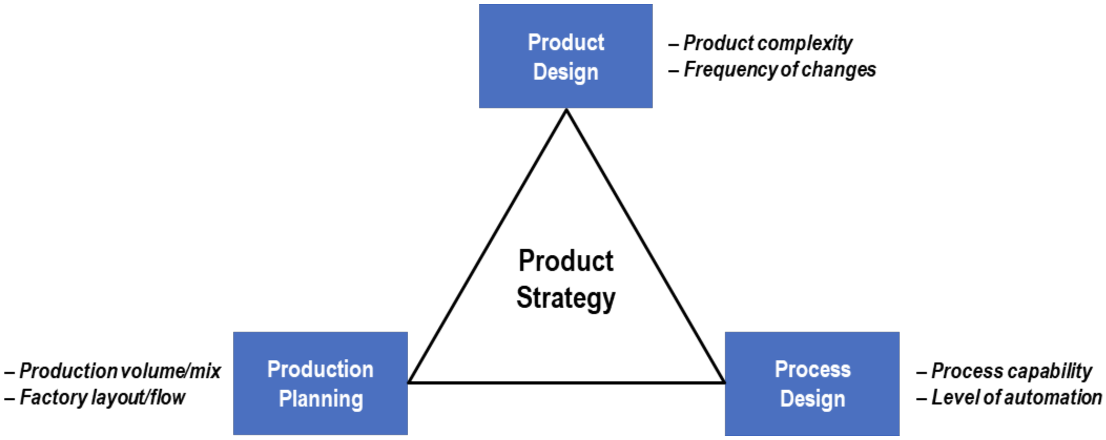


Figure A-1: Inputs to manufacturing system design.

to manufacture various versions of a product or entirely different products in the same factory, then the factory must be designed with this level of flexibility in mind. If the corporate strategy requires rapid product introductions, new technology, or multiple product lines—then factory design is an important consideration. Some of the current crop of large constellation builders are segmenting their factories to support multiple product lines. [2],[3]

Factory layout and flow is determined by production planning requirements. As a result of the product volume and mix, a new factory may be built, or an existing facility may be modified. New factories with "clean sheet" designs are referred to as a *greenfield*. Greenfield designs have advantages over modified facilities because they are not constrained by the existing physical footprint and equipment "monuments." A thermal vacuum chamber is an example of a monument, which cannot be moved once it is installed, potentially resulting in a non-optimal flow. Factory modeling and simulation can be used to explore different production volumes/mixes, layouts, and pinpoint problems before significant capital expenditures are allocated. [2],[3]

Product complexity is a measure of the number of parts, part size and features, levels of assembly in the product structure (a hierarchy also referred to as a *bill of materials* or BOM), number of process steps, and process capability. High-complexity products usually have higher overall costs because of additional steps. More complex products generally require more complex processing; therefore, building simplicity into the product and process design is paramount. [2],[3]

Frequency of changes is another characteristic of highly complex designs. Engineering design changes can occur due to lack of product maturity in the design or as part of a planned major design upgrade requested by a customer. Achieving design maturity early to limit unplanned changes is particularly valuable for HVP. [3]

Process capability is the ability to make a product repeatedly with minimal intervention. The capability of a process is measured by the spread (or distribution) of the process results as compared to the design's specification limits. Specification limits are the allowable upper and lower deviations from ideal target values established by the product design engineer. Processes can produce defects either by having too large a spread beyond specification limits or by shifting the mean (average) of the design characteristic being measured. [2],[3]

Levels of automation refers to the extent to which manual labor is eliminated and reflects conscious choices made to achieve better repeatability, reduced cycle time, improved hardware/personnel safety, or increased product mix flexibility. Automation has little value if an operation is simply accelerated and can lead to process suboptimization. Automation should be used selectively and consider implementation costs, payback period, and integration with an information technology infrastructure. We observed one factory where the only use of a robot was to lift and install one heavy item—an example of judicious use of automation.

Appendix B: Design for Production (DFP)

The design for production (DFP) framework described in this appendix organizes HVP concepts, elements, and strategies observed in other industries that are applicable to satellite production. DFP strategies simplify, standardize, and improve repeatability using robust product designs and optimized manufacturing processes.

DFP Strategies for Product Design

DFP for product design is the engineering practice of designing products that are easy to manufacture. The philosophy of DFP is to "design quality into the product, not inspect or test it in." Each strategy to achieve this is described briefly in this section.

Key product characteristics (KPC) are those product characteristics for which changes can affect the product form, fit, function, performance, and/or safety. Early in the product design phase, design engineers work closely with manufacturing engineers to identify these. **Robust design** methods are used to minimize the causes of KPC variations. The methodology uses parameter design and tolerance design to make product performance insensitive to variations in raw materials, manufacturing, or the operating environment. Tolerances and material grades are selected according to their cost effectiveness. Parameter design methods change the product design to accommodate expected part/process variation, while tolerance design methods change the expected part/process variability to accommodate the product design. The preferred approach is to change the product design (parameter design), instead of tightening tolerances and/or specifying higher grade parts/materials or processes (tolerance design)—based on cost effectiveness. [14],[17],[18],[19]

Design for manufacturing, assembly, and test (DFMAT) focuses on "building in" the manufacturability, easy assembly, and testability into the product from the beginning. The majority of production costs are determined in the early stages of design. When design decisions consider manufacturing during the concept phase, costly corrections can be avoided. DFMAT can minimize total product cost by reducing assembly time, part cost, and the assembly process complexity. [14],[18],[20],[21] Principles include:

- Simplify and minimize the number of parts
- Standardize and use common parts/sizes—minimize part-type variations
- Minimize levels of assemblies (i.e., flatten the bill of materials)
- Design parts for ease of fabrication
- "Mistake-proof" product features for assembly (e.g., permit only one way for parts to fit together)
- Design parts for easy orientation and handling (i.e., symmetry, self-locating features, etc.)
- Design for ease of assembly and automation (where it makes sense; operations people can't do)
- Minimize fasteners—use snap-fit parts (when possible)
- Develop modular designs as building blocks
- Design built-in tests and test access points into each hardware configuration for increased test flexibility
- Include perceptive test-like-you-fly practices to identify interface and performance issues

Design to cost (DTC) emphasizes cost as a design parameter during the development process. DTC ensures that a design meets the stated cost targets by assigning cost to every part in the product structure, then systematically challenging every design element to remove cost. After the “design freeze,” no change is considered unless it reduces cost. For HVP, even tiny cost reductions can make a significant difference to the bottom line. [14],[15],[21],[22]

Highly accelerated life testing (HALT) involves the intentional application of accelerated and combined environmental and operational stresses far above the hardware design limits to accelerate failures to better understand the failure mechanisms. HALT results make the design more robust prior to moving into production. Satellite builders that use HALT have improved first-pass success during subsequent TR-RS-2014-00016 qualification testing. [29]

Technology readiness levels (TRLs) provide a consistent, uniform way to compare the maturity of technologies during the acquisition phase of a program. TRLs are based on a scale from 1 to 9, with 9 representing the most mature level. HVP places greater emphasis on using technology that is mature and properly qualified. [24]

DFP Strategies for Process Design

DFP for process design employs manufacturing engineering practices to enable highly repeatable and efficient operations that yield high quality products. Process design applies structured development methods to define, optimize, and control sources of variation inherent to manufacturing processes.

Key control characteristics (KCC) are the inputs that affect the output of a manufacturing process. To reduce the variation, the impact of the controlled and uncontrolled manufacturing process parameters (e.g., speed, temperature, humidity, etc.) must be understood. Design of experiments (DOE) is a tool that can be used to understand the relationship between these process parameters. A designed experiment can identify the effects of these parameters by optimizing the inputs to determine which KCCs and KCC interactions are statistically significant. KCCs can be monitored by statistical process control (SPC) to ensure the process remains in statistical control. **Variability reduction** and KCCs are central to designing a process that has high repeatability. Without repeatability, defective products create product flow bottlenecks and stop production until the root cause of the defect is determined. [14],[15],[18],[19]

Process Failure Mode and Effects Analysis (PFMEA) is an approach used to identify risks and sources of possible errors in a manufacturing process. PFMEA identifies the ways a process design can fail. A ranking system is used to estimate the severity (S), frequency of occurrence (O), and difficulty of detection (D) of potential process errors. The S/O/D factors are multiplied and result in a value called the *risk priority number* (RPN). The RPN is used to prioritize the failure modes so that corrective actions can be taken. Error-proofing measures are then carefully selected to ensure failure modes are prevented in support of highly repeatable processes. [25]

Manufacturing readiness levels (MRL) assess the maturity of manufacturing readiness, just as TRLs are used for technology readiness. MRLs provide a common vocabulary for discussing manufacturing maturity, risk, and readiness. MRLs are based on a scale from 1 to 10. For space systems, maintaining production flow and avoiding stoppages for rework or retest of flight hardware mean that repeatability and maturity of manufacturing processes is paramount. [26]

DFP Strategies for Production Planning

DFP for production planning must happen before any designs are finalized or metal is cut. Production planning looks at the required production rate and product mix, the layout of the factory, and the product flow.

The **production plan** is based on the master production schedule and the material requirements plan. The master production schedule (MPS) is the timeline for the production of end items (e.g., individual satellites). It breaks down the production plan to show the quantity of each product to be made in each period (typically monthly). The plan identifies end items per month depending on the available capacity. Capacity is then checked to assess whether critical resources (e.g., equipment, personnel, inventory, etc.) are available to support the intended schedule. This creates a material requirements plan (MRP) that explodes the bill of materials (BOM) and details plans for work orders and purchase orders. Differences between the intended production and available capacity must be resolved, either by increasing capacity (i.e., adding shifts, overtime, weekends) or reducing demand. [2]

Level loading is continually producing an amount equal to the average demand. This means a company will use resources at a uniform rate and produce the same amount each day. Level loading is necessary for a smooth production plan that will support contractual requirements that typically contain monthly and cumulative requirements and include an initial time buffer known as a *set-back* (see Table B-1). It removes peaks and valleys in production rate, enhancing schedule predictability. [2],[27]

"Push" and "pull" manufacturing are two fundamental methods to control inventory in a manufacturing environment: Both methods can be used together to support HVP. The principle is to always have the "right part, at the right place, at the right time." Just-in-Time (JIT) methods reduce inventories to a minimum. Work-in-process inventory (units) are "pulled" through the system by request. When a downstream process needs material, it signals an upstream process to replenish inventory. When the MRP breaks down the BOM to the lowest hardware level, it back-schedules work via the release of work orders and purchase orders. Inventory may be "pushed" through the system whether or not a part or component is needed. Integrating JIT systems with MRP to collocate parts/materials/assemblies directly on the production floor (i.e., point of use inventory) integrates both concepts and produces the most efficient result for HVP. [2],[17]

Product flow refers to the balanced synchronization of fixed routings and work content at each work cell that is typical of flow manufactured products. Each work cell produces a dedicated product and utilizes dedicated equipment and tooling. The material flows from cell to cell and uses material handling equipment such as automated guided vehicles (AGVs) or transfer lines. The product flows in a

Table B-1: Notional Example of Level-Loaded Production Plan

Production Requirement: Ship 324 satellites by March 2021

324/14 = 23.14 per month >> Round up to 24 per month

Period of Performance = 14 months (February 2020 to March 2021)

	2020												2021			Totals
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	
Contractual Requirement		20	26	24	22	26	20	24	28	24	24	28	20	24	14	324
Cumulative Requirement		20	46	70	92	118	138	162	190	214	238	266	286	310	324	324
Manufacturing Plan	24	24	24	24	24	24	24	24	24	24	24	24	24	12	0	324
Cumulative Plan	24	48	72	96	120	144	168	192	216	240	264	288	312	324	324	324
	Set-back															

sequential manner among cells with little work-in-process inventory.

Creating a **minimum travel factory layout** is critical when designing for an HVP flow. To achieve this, there are several key considerations. Product flow follows a routing that mimics the product structure. Travel distances between operational steps are compressed to utilize a footprint as small as possible. Operational steps are designed to be performed in “equal amounts of time” to support synchronized flow. All equipment, tools, and inventory are colocated in the work cell at the point-of-use. The flow of the product should not contain any constraints or bottlenecks and be designed for maximum efficiency (i.e., minimal waste). [15],[16],[17]

Factory modeling and simulation uses computer models to analyze and optimize a factory or production line before the facility is built. This allows many configurations to be tested for bottlenecks, resources required, and to validate operation logic. The sensitivity of overall production to changes in each of these attributes can be measured. Simulations can assess the system’s performance by statistically and probabilistically reproducing the interactions of all the components for a predetermined period of time. Inventory, assembly, transportation, and production can be assessed within a simulation model, preserving and improving efficiency at the lowest possible cost. Virtual manufacturing simulations can even show the factory in a 3-D immersive environment. [28]

Appendix C: Acronyms/Abbreviations

AGV	automated guided vehicles
AI&T	assembly, integration, and test
BOM	bill of materials
CONOPS	concept of operations
CPA	Continuous Production Agility
DFMAT	design for manufacturing, assembly and test
DFP	design for production
DOD	Department of Defense
DTC	design-to-cost
ERP	enterprise resource planning
GPS	Global Positioning System
HALT	highly accelerated life testing
HVP	high-volume production
JIT	just-in-time
KCC	key control characteristic
KPC	key product characteristic
LEO	low Earth orbit
MPS	master production schedule
MRL	manufacturing readiness level
MRP	materials requirements planning
NRE	non-recurring engineering
NSS	national security space
PFMEA	process failure modes and effects analysis
RPN	risk priority number
TRL	technology readiness level
WIP	work-in-process

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