ENPULSION
SPACECRAFT TECHNOLOGY

THE INDUSTRIALIZATION OF PROPULSION SYSTEMS

DISRUPTING AN INDUSTRY

A CASE STUDY

CONTENTS

CASE STUDY ON THE INDUSTRIALIZATION OF PROPULSION SYSTEMS FOR CONSTELLATIONS

A practical example on how to achieve high production rates and low product costs without compromising on heritage quality requirements.

BACKGROUND

Having evolved into a viable market, the majority of business cases based on Micro- and Smallsats are based on constellations. Rate of production as well as streamlined integration become key drivers for success and result in flow down requirements for all subsystems.

Traditionally, this has proven to be particularly demanding for a propulsion subsystem, due to complexity of most propulsion subsystems, which in turn drives the complexity of integration, as well as strong dependability of propulsion design on mission requirements. Especially the latter has led to one-akind implementation of propulsion systems, and therefore complex implementations, long leadand cycle times, and therefore increased cost.

MODULAR SOLUTIONS

To counter such issues and comply with constellation production rate and implementation requirements, ENPULSION has introduced a modular, universal building-block based propulsion technology which is designed for high rate production.

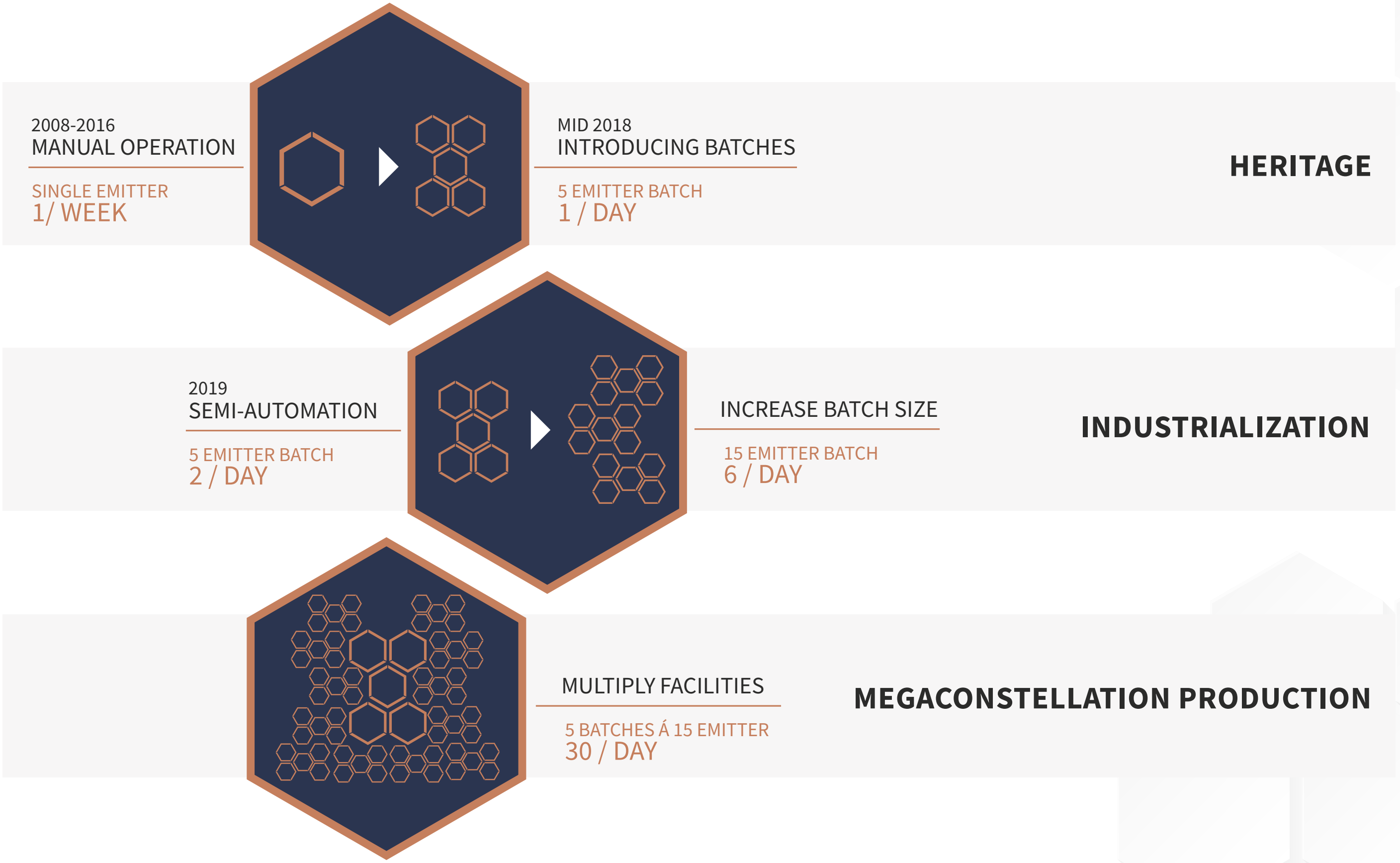
This IFM thruster technology has been successfully industrialized and is currently delivered to customers at unmatched rates between 2 to 5 flight propulsion systems per week.

SCALING PRODUCTION CAPABILITIES

ADAPTION

Based on a product designed for high rate production, ENPULSION has implemented an adaptable production line, that enables different scalability steps. Based on a heritage laboratory process of thruster production, a first scalability step has already been performed by the introduction of batch processes, increasing production capability from 1 ion emitter per week to 5 per week.

Introduction of statistical evaluation of ongoing production processes, optimized selection at early production steps and semi-automatization allows scalability to 2 emitters per day. Further increasing batch sizes by scaling production equipment at the existing production facility allows for production rates of 6 emitters per day. The possibility for further scaling of such a model fabrication line by direct multiplication of facilities and corresponding scaling of support processes makes this concept adaptable to megaconstellation production rates.



Scalability of ENPULSION production line


ENPULSION
ENPULSION
ENPULSION

PRODUCT ASSURANCE AT HIGH PRODUCTION RATES

AGILE PROCESSES

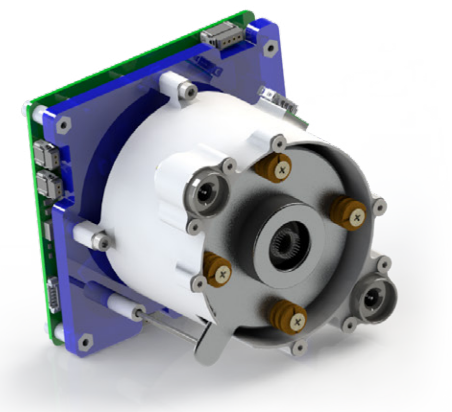
There has been a general perception within the New Space Community that increasing production rates to constellation requirements together with cost pressure necessarily leads to a tradeoff against heritage product assurance standards (e.g. ECSS), given the significant time and effort required to include implementation of such standards.

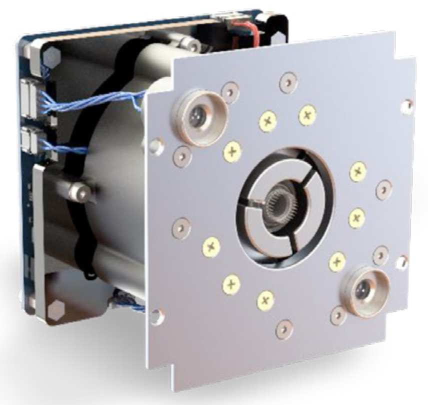
In contrast, ENPULSION has been successful in implementation of heritage quality processes within the current high rate production rate, based on an agile implementation of traditional product assurance (PA) processes.

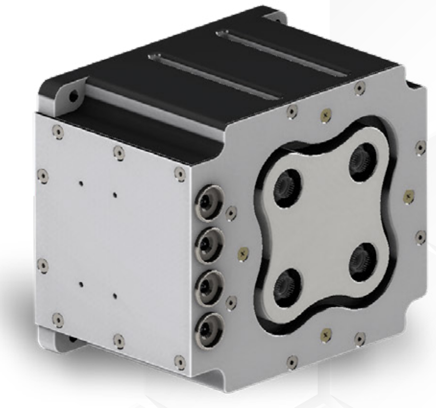
With focus on optimization of PA process execution, the additional implementation effort is compensated by the large number of systems produced. The definition and design of the agile implementation of heritage PA processes has been guided and complimented by a direct dialogue with space heritage providers to find optimized implementation complying with both stringent requirements and series production mindset.

FINDING THE PERFECT TOOLS

Optimization of mandatory inspection point (MIP) loops allow implementation with minimum delay by designing the production and testing flow adaptable in a way so that flagged hardware can be taken out of the manufacturing flow and reintroduced after customer decision. This is complemented with a choice of proper tools, both digital and measurement systems, which are both optimized for high throughput, short cycle times and digital implementation.

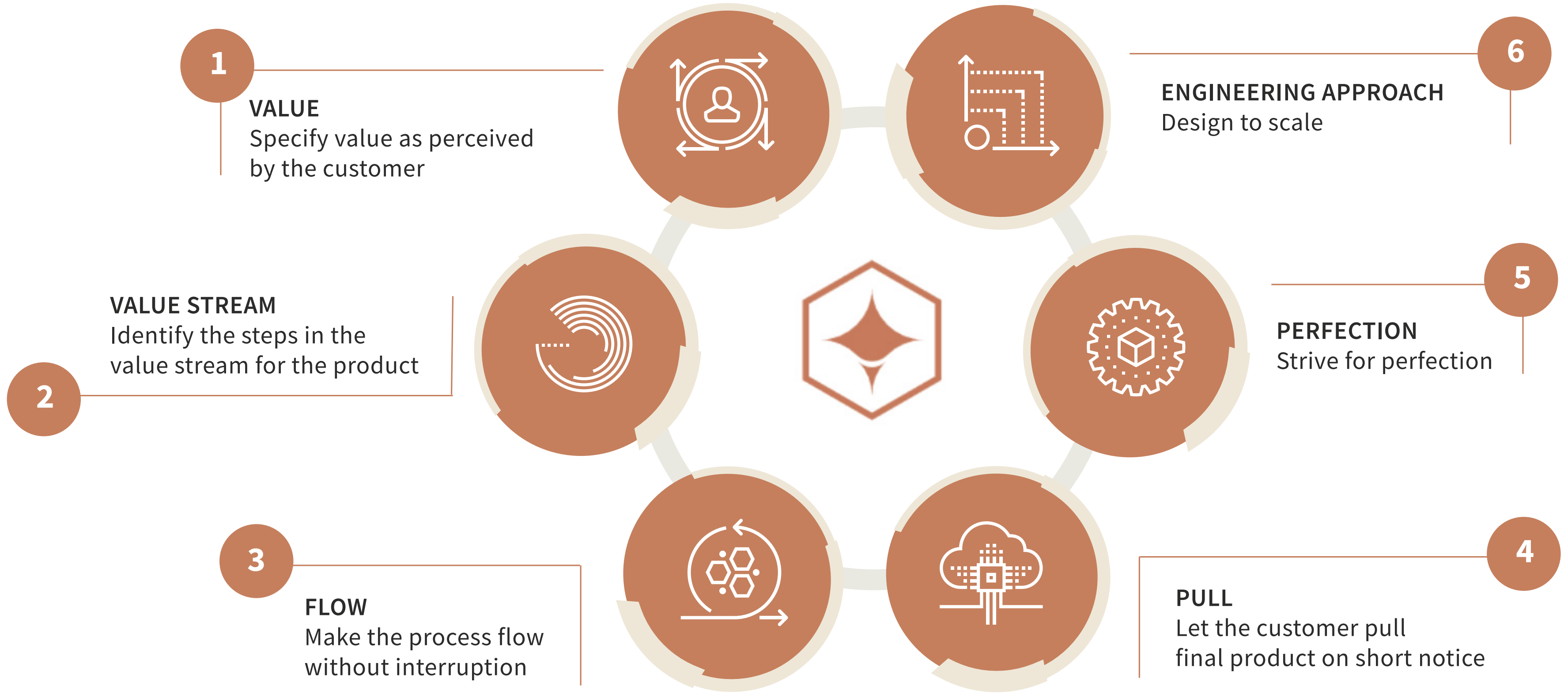






An example for such implementation is an automatized incoming inspection tool that enables parallelized inspection of up to 100 parts, fast measurement cycle times compatible with the production flow and automatized non-conformance reporting implementation for optimized feedback loop to suppliers, therefore enabling 100% inspection at current and planned production rates.

LEAN MANUFACTURING IN THE SPACE INDUSTRY



6 steps of lean manufacturing at ENPULSION high rate space propulsion production

MODULAR DESIGN

To accomplish high throughput production without trading cost versus quality, a lean manufacturing approach has been introduced into the ENPULSION manufacturing philosophy. In this approach, the five classical steps of lean manufacturing are expanded by a dedicated engineering to scale step, that highlights the importance of incorporating scalability into early product development. Key **value** for the customer is generated by a modular, **high performance propulsion technology** that combines high capability (large total impulse and high impulse density), high adaptiveness (throttling in specific impulse and thrust), modularity (used as standalone thruster or in clusters enabled by bus design), as well as attractive price point, both in direct cost (fixed low price offer) and reduced integration cost enabled by solid, inert propellant and fast delivery cycles of two months or lower.

This value generation is succeeded by **value stream** analysis, analyzing required production steps and flow for design throughputs with according buffers, including the identification of bottlenecks and impact. Such analysis needs to be concluded to a level of detail where for example the screw-locking of a glue is divided into the amount of minutes it takes an employee to mix the glue for one batch of thrusters, then the amount of minutes he takes per thruster to apply the glue, the amount of minutes he or she takes to load the thrusters into a curing oven and then the process time of the oven used for curing the glue.

Based on this, the production line is optimized for uninterrupted **flow**, adjusting bottleneck process steps and culminating in the finalized production layout. The resulting ENPULSION production line is a pull-based manufacturing line, in which subassemblies are produced independent of customer projects up to late assembly stages, enabling shortened customer cycles.

By placing orders, **customers pull** requested thrusters in suitable configuration from the pool of pre-assembled and stored thruster parts, triggering the final assembly and acceptance test flow. This manufacturing line design allows total thruster cycle times including final assembly and standardized acceptance testing within two weeks, generating unmatched short delivery cycles.

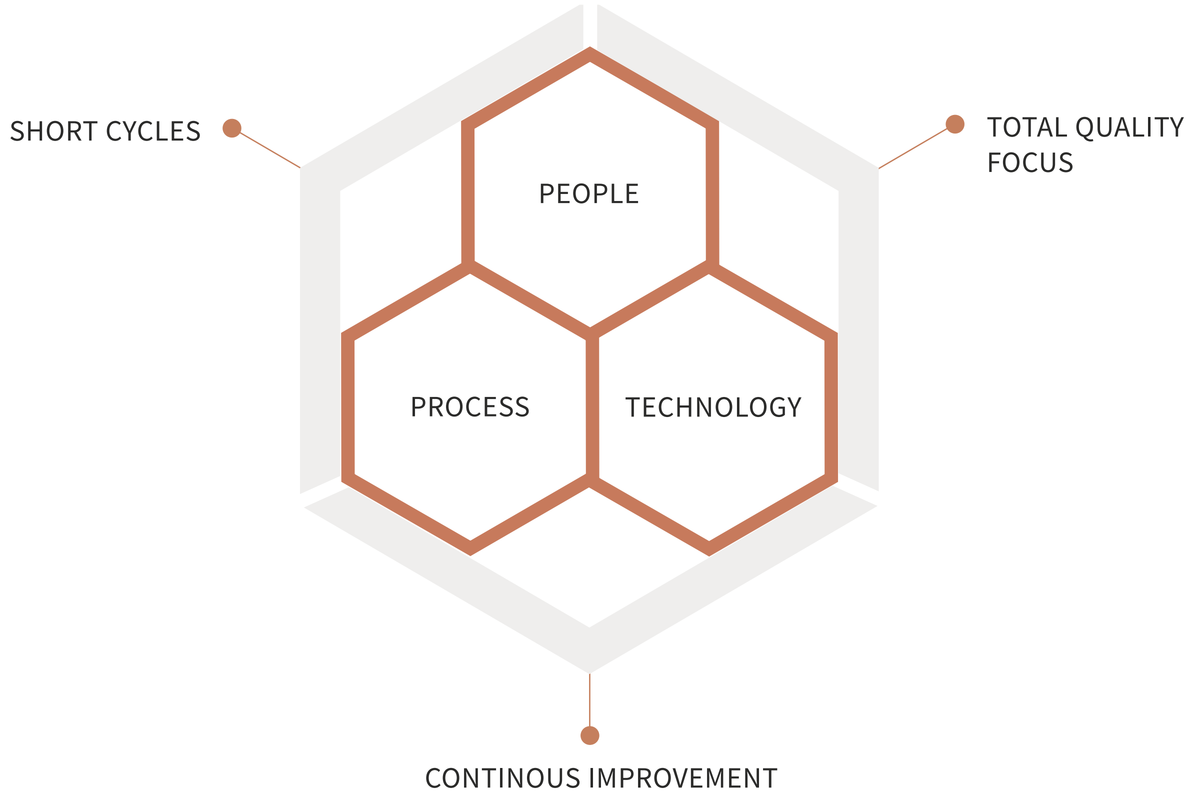
LARGE-SCALE PRODUCTION APPROACH

Within the entire manufacturing process, the agile implementation of heritage quality processes based on inspection point principles that are seamlessly into incorporated in the production flow as well as tools to continuous improvement result in high quality of delivered products as well as continuous improvement of the production line satisfying the teams **strive for perfection.**

These classic steps of lean manufacturing are based on a complying **engineering approach**, which introduces the mindset of large-scale production into the early stages of product development and design stages.

ENPULSION thruster products are designed in a modularity manner both on thruster and subsystem levels, and scaling between thruster products is accomplished by a philosophy of multiplication of core components and processes. This not only allows to maintain heritage of key components on a technological basis but is also in-line with the batch-based production line design.

IMPLEMENTATION IN THE ENPULSION MANUFACTURING PROCESS



Implementation of lean manufacturing principles

CONTINUOUS IMPROVEMENT

Engineering processes at ENPULSION are designed in accordance to this lean manufacturing philosophy, linking the key areas with corresponding focal points. In the interaction between processes and technology, the focus is laid on continuous improvement.

The interaction between people and processes is focused on short development cycles, whereas the interface between people and technology is dominated by a focus on quality.

1 **INCOMING INSPECTION**
Batch inspection enables 100% incoming inspection, direct supplier feedback loop for continuous improvement

2 **EMITTER PRODUCTION**
Batch processing and semi-automation to increase throughput

3 **PROPELLANT LOADING**
Batch processing and semi-automatization to increase throughput

4 **EMITTER CHARACTERIZATION**
Parallel batch testing
Pre-selection data

5 **SCANNING & PRE-SELECTION**
Pre-selection based on statistical models from production allows early stage selection and continuous improvement

6 **FINAL ASSEMBLY**
Streamlined pull processes decrease cycle time customization options

7 **THERMAL ACCEPTANCE TESTING**
Parallel batch testing incorporating customer acceptance requirements

8 **VIBRATION TESTING**
Parallel batch testing incorporating customer acceptance requirements

9 **FUNCTIONAL ACCEPTANCE**
Parallel batch testing and semi-automatization reduce average process times

10 **FINAL INSPECTION & SHIPPING**
High rate processes developed with customer feedback loop

Manufacturing flow at the ENPULSION production line

Based on these principles, the manufacturing process and scalability for IFM thrusters at ENPULSION can be discussed. In **step 1**, automatized incoming inspection optimized for design throughput, short non-conformance reporting with direct link to suppliers enables compliance with high heritage quality processes, 100% part inspection and engineering feedback, while allowing the required high throughput.

In **step 2**, emitters, which are the core component of the IFM technology, are manufactured from incoming parts. These complex manufacturing steps are performed in parallel batches, including aligned inspection plans, to achieve nominal throughput.

The same scaling principle applies to **step 3**, in which the propellant is loaded into the emitter in a complex vacuum process. The semi-finished emitters are then scheduled to undergo a first characterization testing in vacuum facilities in **step 4**, in which average process times, such as evacuation of production chambers, are decreased by testing in batches and automatized test scripts.

Steps 2 to 4 strongly benefit from the design to scalability approach of the IFM technology, which results in significant share of subassemblies across different thruster products.

In a **further step**, emitters are characterized using topology scanning methods and gathered data is used to establish performance predictive models assisting emitter selection for early identification of unsuited emitters.

Selected emitters are stored together with all other preassemblies ready for final thruster assembly which is initiated by customer pull in the requested configuration. The streamlined design of the thruster allows short assembly times within hours, enabled by the Kanban based manufacturing flow.

After final assembly, thrusters are undergoing acceptance testing in **step 7**, which can incorporate customer provided mission realistic test levels, and is performed in batches. In a next **step 8**, the thrusters are undergoing vibration testing, which is again conducted in parallel to increase throughput, followed by final functional firing testing in vacuum facilities in final **step 9**.

Throughout **steps 7-9**, thrusters are assigned to customers, and fully digitalized non-conformance reporting using agile processes and rapid decision cycles are in place, with a replace philosophy in case of major non-conformances.

Step 10 is a streamlined final inspection, packaging and shipping step, in which a standardized process together with close cooperation with logistics partner allow a maximum on flexibility as well as minimum process times. Shipping specifications and packaging has been developed with significant input from customers to align with respective receiving and incoming inspection processes.

CONCLUSION

ENPULSION has successfully introduced a high rate production of a high-performance electric propulsion technology. Based on value stream analysis, a scalable production line design has been implemented that scales to mega constellation production rates. Lean manufacturing philosophy allows to implement a product lifecycle philosophy that combines New Space agility with heritage quality processes, while providing high customer value in terms of product performance, cost reduction and short cycle times.

It can be assumed that this example is largely representative for the industrialization of any other propulsion technology that is planned to be made available for large constellations. The presented case study is however benefitting from the fact that the used FEEP propulsion system is lacking any fluid, pressurized or toxic propellants and the evaluation of additional means to handle such propellants and tanks in integrated gas-based propulsion systems are therefore not included in this discussion.