LEAN PRODUCTION AND INDUSTRIALISATION OF SPACE MECHANISMS

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ABSTRACT

In recent years cost has become an increasingly strong driver for spacecraft programs. There is an increase in the number of players in space, at Operator, Prime and Equipment levels, and this creates a need to be efficient and competitive – whilst maintaining quality – that flows down the supply chain. And this trend shows no signs of stopping.

The primary means by which space equipment, and in particular mechanisms, can lower costs whilst maintaining (or even improving on) quality and reliability, is to standardise; to move away from bespoke designs and build recurrent products with larger production volumes and longer life cycles, incorporating and utilising existing off-the-shelf philosophies historically seen on commercial consumer products.

Recurrent equipment and processes also allow for the implementation of Lean and Just-In-Time production, which are able to further refine the efficiency of production, deliver cost savings and improve on quality.

Mechanisms are invariably mission-critical equipment, with a need for the highest levels of quality and reliability, and this introduces certain challenges. Fault detection and root cause investigation requires a high degree of time and focus, and this can slow down response times and put a hold on production for that and others flight units. Involvement of the customer chain during non-conformance reviews may augment this effect.

This paper discusses the benefits and challenges of industrialisation and Lean methods and principles on space mechanisms, and presents the experiences and metrics gained from the case study of the Antenna Deployment and Trimming Mechanism Mark 2 (“ADTM Mk2”) product.

1 INDUSTRIALISATION

Industrialisation of a product is the establishment of robust processes and systems to allow for efficient and repeatable production at increased volumes.

The first step towards industrialisation of a mechanism is standardisation. Standardised designs (for one single product or across multiple products) will allow for the shared use of ground support equipment. Standardised interfaces (e.g. harness design, mechanical interface plates, etc.) will reduce the number of variants within a product, reducing the complexity of the production process, reducing the possibility of errors occurring, and reinforcing the interchangeability of flight units.

Common building blocks – whether single components or whole sub-assemblies – will enable modular product design, possibly shared amortisation of non-recurring expenses, as well as shared procurement activities with greater purchasing power.

Economies of scale are key to industrialisation. Larger production volumes allow for batch production, and this has many positive flow-on effects. This enables the re-use of standardised mechanical and electrical ground support equipment, which can be amortised over the large number of flight units and spacecraft projects.

Batch production provides the ability to hold batch reviews (e.g. Manufacture Readiness Review, Materials, Part Control Board, etc.) and subsequently generic pro-forma production and acceptance reviews (e.g. Kit Inspection, Test Readiness Review, Test / Delivery Review Boards, etc.). Procurement of sub-assemblies and components can then be done in a similar manner, which increases buying power and helps to reduce costs and improve quality.

Batch production can be structured so that each batch begins with a proto-flight model unit. This provides a structured approach for small design evolutions to be introduced and validated without the need for larger delta-qualification activities. Furthermore, periodic proto-flight models can act as an ongoing quality screen for parts, materials and processes, which will contribute towards improving overall quality and reliability for the product.

Larger volumes of recurrent mechanisms improve on quality as it allows for a more robust second closure process. Statistically, a greater number (and variety) of quality issues is likely to occur over a large-volume build compared to one-off or low-volume builds; these non-quality topics, when in occurrence, can be detected, recovered and flown back into the design. It is reasonable to suggest that engineers may be more willing to implement second closure if they know that it will be implemented on flight hardware as opposed to the simply recording in a lessons learnt system. An ongoing recurrent product therefore supports the convergence of non-quality to low or zero levels and it encourages prevention and mitigation to be put in place for future units.

2 LEAN AND JUST-IN-TIME PRODUCTION

Note that there are many slightly varying versions of Lean and Just-In-Time, particularly regarding terminology. The version discussed within this paper is in line with the training provided to Airbus Defence and Space Ltd. by an external Lean consultant, and the activities performed with that consultant on the Antenna Deployment and Trimming Mechanism Mark 2 (“ADTM Mk2”) product.

2.1 Lean Production

Lean is a framework, a mindset and a systematic approach applied to manufacture (or to any process that comprises a set of discrete process steps) to remove ‘waste’ with the aim of making reductions in cost and schedule, and improving quality. The philosophies and methodologies of Lean originated in Japanese manufacturing and most notably from the automotive sector.

Lean was traditionally viewed as an approach that could only be applied to 1) the consumer goods sector, and 2) high-volume production. The idea of a ‘production line’ conjures up images of large automated factories rapidly churning out products – an image not usually associated with the production of space hardware. Consequently, the space sector, where volumes are low, product complexity can be high and reliability is paramount, had not been an apparent application for Lean.

Lean however is flexible and is able to be applied to any volume of production and for any size and complexity of product, from one thousand cars per day to several spacecraft per year. The only pre-requisite for the implementation is that the process is a series of steps or sub-processes. Space hardware production lends itself well to Lean implementation by being thoroughly process driven, be it for design, build, test, documentation or reviews.

The needs of the customer form the focus of Lean. There are similar stakeholders between the commercial consumer goods sector (e.g. the automotive industry, the origin of Lean) and the space sector; that is, a customer (or chain of customers), design standards, regulatory authorities, etc. Whilst the complexity and scope of the customer needs (i.e. requirements) may be higher within the space sector, the outcome is the same: whatever contributes to what the customer requires adds value and whatever is not value adding is considered ‘waste’.

2.1.1 Waste

Waste within the production process is classified as either ‘obvious’ (it is not necessary and can be removed, e.g. over-testing) or ‘hidden’ (it is necessary and cannot be removed, e.g. some transportation / movement) and can be defined within seven categories:

- Inventory (too much work in progress or stock)
- Transport (travelling with the hardware); for example, consider the cleanliness processes that go into transportation of hardware.
- Movement (travelling without the hardware)
- Waiting Time (operator waiting for the hardware or vice versa); for example, hardware waiting for customers attendance at inspections and reviews
- Space / Surface Area (inefficient usage of available space)
- Rework / Defects (non-conformances and the cost of non-quality)
- Overproduction (production rate not aligned with customer needs).

There may also be waste within the equipment design itself (e.g. functionality not required, large design margins, etc.) however the implementation of Lean is more focused on the production process to deliver that design.

Tools such as Value Stream Mapping (“VSM”) can be used to help remove waste from the production process. The ‘current state’ is mapped out and can then be reviewed, waste removed and restructured into a ‘future state’.

2.1.2 Continuous Improvement

The implementation of Lean to a product line is not a single one-off event but rather an ongoing process. As such, it is important that the entirety of the team (from the build and test technicians to the design engineers, production and project managers) possess the correct mindset of Continuous Improvement (Japanese term “Kaizen”).

Continuous Improvement is the ongoing daily effort by the whole team, to maintain and improve the production process, filling in the gaps between occasions of larger innovations or Lean implementations. Continuous Improvement mirrors the

Quality systems within the space sector with the key message: quality is within everything we do and is the responsibility of everyone.

2.2 Just-In-Time Production

Lean production can be achieved through the implementation of the Just-In-Time production and its principles.

Traditional (or Just-In-Case) production is driven by the 'ability to deliver' and characterised by high levels of inventory. The company produces faster than needed, using the surplus output as a buffer to mitigate risks in the future. Just-In-Time production is driven by the 'ability to react' to changing customer needs and market conditions, and is characterised by low 'throughput time' – this is the total duration of production from start to finish. This approach mitigates the risk of stock that can't be used and ensures that customer needs are met.

The ability to deliver has always been a driver for space projects; spacecraft need dates, launch windows, contractual delivery dates, etc. compel both prime and sub-contractors alike to ensure that products are built, tested and delivered on to the next level. This is perhaps more pronounced with bespoke equipment, which comprises larger schedules covering additional mission phases from early design, qualification through flight unit build, test, integration, etc. Changes *shouldn't* occur after CDR, and it is anticipated that the procurement and build phases would not be affected by those changes.

Conversely, for recurrent equipment it is entirely likely that requirements could change well into the product life, when many flight units are built and work-in-progress builds are underway. Evolving technology is a strong example where the ability to react is important; e.g. the industrial shift towards Electric Orbit Raising, where existing stock of equipment that is not compliant with the revised environmental and life requirements may need to be modified or might never be used at all, with adverse commercial effects.

Inventory and work-in-progress also presents a risk with regards to non-quality. For example, if a particular component, installed on a number of completed flight units, was found to be faulty and consequently quarantined. Inventory means that more completed flight units may need rework to satisfy 1st or 2nd closures.

The term Just-In-Time itself refers to the delivery of the required product to the customer when they require it, and can be defined by the 5 R's: the right part in the right quantity, of the right quality, at the right moment in the right place.

There are four principles of Just-In-Time production: Pull, Flow, Takt and Zero-Defects. The combined implementation of all four of these principles allows for improvements to, and synchronisation of, the production line to happen. This is represented by the symbolism of the 'temple of Lean', as shown below, where the principles form the four pillars of the structure.

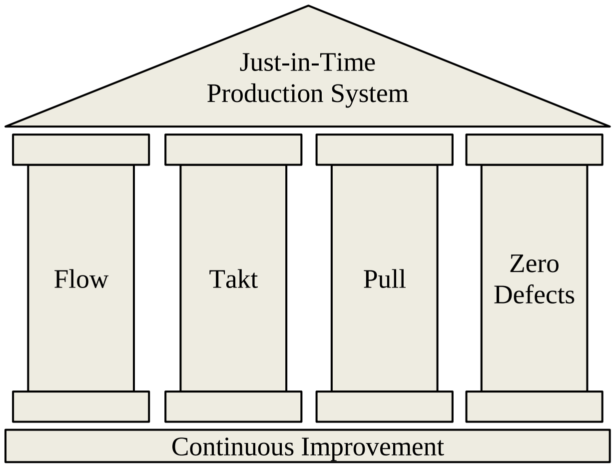

Figure 1. The 'Temple of Lean'

2.2.1 Flow Principle

The Flow principle involves achieving the production flow by restructuring the processes in a logical manner; both in the process structure and in physical terms.

Flow within the process can relate to the logical structuring of sub-assemblies on the equipment's Bill of Materials ("BOM") and identifying the appropriate point in the process to introduce and integrate them into the equipment general assembly; for example, the use of a 'fishbone' assembly structure where all sub-assemblies flow into the main assembly line. This particularly benefits equipment featuring variants, where logical modularity can streamline production.

Physical flow relates to streamlining the physical transportation of the hardware from one process step to another. Any transportation of mechanisms hardware presents some level of risk, and transportation outside of clean production areas presents additional cleanliness and contamination risks. Reduction in the hardware transportation (both in the number and length of trips) will reduce the risk to hardware and reduce obvious waste (transportation and movement).

2.2.2 Takt Principle

The Takt principle involves setting production pace to meet the customer needs, and achieving production rhythm by levelling the work content. The word ‘Takt’ itself is German for the baton that a conductor uses to instruct and regulate an orchestra, and represents a time rate and indeed the ‘heartbeat’ of a production line.

The ‘Takt time’ is the rate at which a new build should begin (i.e. Kit Mandatory Inspection Point (“MIP”)) and at which a complete product should – in the original automotive context – roll off the line and out the door (i.e. Delivery Review Board (“DRB”)). Within the process flow the Takt time represents the period with which standard cycles of work should repeat and the hardware should move on to the next cycle of work content.

Customer demand for geo-telecoms mechanisms is characterised by the rate at which spacecraft are won (and then produced). For example, assume that four telecommunications spacecraft are produced per year. If the production rate at platform level is uniform, then it follows that one complete set of flight mechanisms should be delivered every three months. Therefore, each mechanism should be delivered at a rate (‘Takt time’) equal to three months divided by the number of units per fight set.

In the real-world industry environment the customer need is not so simple and is not fixed. For example, additional (or fewer) spacecraft may be required. This capacity is taken into account formally as a customer ‘need’ within contractual requirements and batch works orders.

Levelling of work content is performed by ensuring that each cycle of work content fits within the allowed time – no operators / machines are under-utilised or overloaded, and the hardware does not wait for the operator / machine (shelf time).

Within the Just-In-Time planning, additional margins should be included in order to accommodate for the slower cycle times associated with the processes involved in mechanisms production.

2.2.3 Pull Principle

The Pull principle involves providing the parts to the downstream process only when they are required. Hardware is delivered based on actual inventory levels and needs instead of predicted future demand.
Every process step should be considered as a supplier and the subsequent step as its customer. The hardware should only be passed on to the customer when they require it, and consequently the onus falls to the upstream process to store the hardware until the downstream process is ready to receive it.

Note that ‘ready to receive’ does not only mean that the operator or machine is available to perform the next process. Physical accommodation should also be taken into consideration; that is to say, is there a safe, fit-for-purpose location for the mechanism to be placed, so that it is not at risk of harm (physical, cleanliness and contamination, etc.).

2.2.4 Zero-Defects Principle

The Zero-Defects principle involves improving and stabilising all processes. It has two aspects: a fault management process loop and Total Productive Maintenance.

The former, fault management, consists of a loop of fault recognition, feedback, correction and prevention. This system should be immediately familiar to mechanisms engineers as it mirrors our standard non-conformance and Quality processes (albeit with different terminology). All space equipment is already subject to this methodology as part of established industry process: non-conformance detection via inspection or test (recognition), non-conformance reporting up the customer chain (feedback), 1st closure and hardware recovery (correction), and finally 2nd/3rd closure and lessons learnt (prevention).

The latter, Total Productive Maintenance, involves maintaining and improving the production through the machines (ground support equipment), facilities, employees, and anything that adds value to the product. This comprises continuous upkeep of all support equipment (e.g. equipment calibration and inspection regimes) as well as training and certification of staff.

Zero-Defects can be implemented through various means, both within the equipment design and within the production processes; for example, the use of techniques such as poka-yoke to remove the possibility of human error occurring.

Within the context of mechanisms production the aim of the Zero-Defects principle is to continuously reduce the amount of non-conformances (ideally to zero) and consequently reduce the associated cost of non-quality.

2.3 Implementation Challenges and Lessons Learnt

Being that Lean and Just-In-Time originated from commercial consumer goods sectors it followed that only the physical product was what the customer wanted (and the only value adding component). It is important to keep in mind that a mechanism is not just the hardware but also the data packs, reviews, etc. – and these are all captured as customer needs within the product and specific specifications, statements of work, etc.

There are many hurdles encountered when attempting to implement Lean and Just-In-Time onto mechanisms (or any space equipment) directly from theory. Some key challenges are discussed here.

The first main challenge is qualification. This philosophy of validation by demonstration, of proven or justified design and processes, is a foundation of spacecraft engineering and should be strictly adhered to in order to ensure that quality and reliability are maintained. The drawback to qualification however is that it becomes difficult to introduce any design or process modifications; even seemingly benign changes should always be assessed with due levels of scrutiny. Whilst this may not prohibit implementation, it does shift the focus from modifying existing processes to keeping them unchanged but restructuring them in a more effective flow.

If any changes to process or design are to be made, then agreement with the customer chain should in most cases be sought before any further action can be taken. The changes would then need to be validated and/or justified (test, analysis, similarity) and appropriate documentation amended to capture the traceability. It is immediately apparent that these processes might hamper the desire to make any changes.

The next significant challenge to implementation is anomaly investigation and recovery. Just-In-Time production is built on a structured, synchronised and time-based system. Occurrences of non-quality need to be dealt with swiftly otherwise they will halt the production line (so that the rhythm and synchronisation is not interrupted). Small process-related issues within mechanisms production can generally be rectified quickly however occurrences of non-quality are treated with significant scrutiny due to the criticality of the equipment for the mission.

As described earlier, mechanisms are subject to robust Quality and non-conformance management processes by virtue of their performance requirements and mission criticality. Any non-conformance must be investigated and assessed for disposition. The appropriate non-conformance reviews must be held and agreements on ways forward need to be reached, which is likely to reduce the speed in which the topic is progressed, particularly if actions are generated from these reviews. Even first closure (direct recovery for the unit) may take a significant amount of time to complete. If second closure affects other flight units, then the impact of a single occurrence is spread much further. This impact on the time to resolve non-quality is further amplified if additional levels of the customer chain are included as part of the review process.

Customer interaction, as suggested above, is a major impediment to the operation of a Just-In-Time system; the main reason being that it removes a level of control (in schedule and in decision-making) from the production team – something that doesn't exist in commercial consumer goods sectors – and being in control of the production is paramount for operating Just-In-Time. Good planning and the use of generic 'boiler plate' review templates can reduce this impact for standard reviews.

Customer involvement can generate additional unplanned work for a number of valid reasons, via specific requirements, actions from reviews or anomaly investigation activities. Apart from the obvious cost impact, unplanned work is in direct conflict with the philosophy of Just-In-Time production, where the entire process should be well known, understood and mapped out.

Intuitively, the idea of batch production is contrary to the Pull principle. However, here a batch refers to a customer order for a certain quantity of flight units over a certain period of time – allowing for the derivation of delivery rates and Takt time. The batch order merely is a renewal of the payment and cash flow structure to allow the production to continue, and generally one batch begins when the previous one ends, providing a continuous production run. Within the production line the hardware still proceeds under one piece flow.

3. CASE STUDY – ADTM MK2 PRODUCT

The Antenna Deployment and Trimming Mechanism Mark 2 ("ADTM Mk2") product was created for the Eurostar 3000 platform with the view to be high-volume industrialised mechanism. Efforts were made early in the product life or even from the qualification campaign to put this into effect; for example, through test automation and maximising facility utilisation rates.

In 2012 Airbus Defence and Space Ltd. engaged with an external Lean consultant to implement the philosophies and practices of Lean and Just-In-Time production to the mature product, in an effort to further industrialise the mechanism. Whilst the product line already included in excess of 30 flight units (with nearly as many operating in orbit) over two production batches, the process was not optimally structured and was aligned more towards Just-In-Case than Just-In-Time.

A set of Key Performance Indicators ("KPIs") were selected, which characterised the performance of production for this mechanism:

- Delivery rate (budget tracking)
- Throughput time, reflective of overall spend (e.g. 'marching army' costs)
- Number of non-conformance reports ("NCRs") per flight unit
- Facility utilisation rates

A workshop was held with an integrated team built up from all appropriate functions (design engineering, technicians, quality, production control, etc.). Value Stream Mapping work was performed with a waste identification and removal exercise. The team reorganised and synchronised the production process and the shop floor layout was physically restricted to support the revised production flow. Visual management systems such as an 'Obeya' board were set up in order to support the running of the production.

The work was done prior to the kick-off of the fourth production batch (containing 32 flight units). The final KPIs were measured from this batch following its completion.

Table 1. Comparison of Key Performance Indicators

	Initial	Goal	Final
Batch	1 and 2	3	
Delivery rate (units per month)	Variable, 1 – 3	4	4
Throughput time (months)	Variable, 8 – 24	≤ 5	4.5 – 7.0
NCRs per unit	3	≤ 1.0	0.9
Chamber utilisation	1 out of possible 10	8 out of possible 8	7 out of possible 8

Due to the challenges discussed earlier in section 2.3 the implementation within Batch 3 could not be achieved perfectly in line with the planning. Some fine tuning of the process was required whilst the production was ongoing, and the results were fairly close to achieving the goals that were set prior to commencement of the production batch.

4. CONCLUSION

This paper has broadly discussed the topics of industrialisation, the principles of Lean and Just-In-Time production systems, difficulties in their implementation and finally the results of a case study on a mature mechanism.

It has been suggested that these concepts, philosophies and methodologies can be powerful methods to reduce costs and improve quality, and generally to improve competitiveness. It is also important to understand that a tailored approach is needed when applying established philosophies, approaches and tools that originate from the commercial consumer product sector.