Industry Project Management Tools for Nanosatellite Teams

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1 Abstract

Space systems projects continuously search for methods for Faster-Better-Cheaper projects, with lessons learned calling for more frequent testing, team communication, concurrent engineering practices and commercial-off-the-shelf (CotS) components. While most space missions can take decades to develop, nanosatellites provide a small-scale platform with short development periods that allow for experimentation for different tools for project completion.

ManitobaSat-1 is one such nanosatellite project, aiming to design, build, and launch a 3U nanosatellite by 2021. To find ways to improve systems engineering and project management methods for nanosatellites and the space industry, the ManitobaSat-1 team is testing industry-leading methods and tools originating from Agile Philosophy, Concurrent Engineering, Lean Manufacturing, and Theory of Constraints. These methods have been used in conjunction with visual work management tools at a variety of non-space systems manufacturing companies and have shown significant reductions in development times. By enabling real-time visibility of workflow, the blockages are immediately visible and enable corrective actions to be carried out before delays occur.

Other sources of project delays are risk and non-conformances late in the life of a project, when corrective actions come at a higher cost. Risk management work can be supplemented by hardware testing to mitigate non-conformances. Additive manufacturing allows for early physical testing, allowing for corrective actions when they have a low impact on budget and scheduling. This work presents tools available for space systems projects to manage risks and non-conformances.

2 Background

The space industry has been slow to adopt new innovation, refusing to adopt new technologies and methods to avoid uncertainties and perceived risks. The pursuit of the safest method that has been done in the past can make engineers complacent, letting opportunities slip by. Methods for project management have largely remained unchanged since the time of the space race. At that time, the space environment was mostly unknown and uncharacterized; this meant that space missions carried a huge amount of risk. Traditional project management tends to be risk adverse to ensure the safety of their resources, but it reduced the ability to exploit opportunities, or implement new technologies. In the event that changes need to be made to the project, traditional project management will attempt to stick to the original, inflexible plan. This aversion to adapting to new situations can incur rework, pushing the schedule and cost.

As space programs matured, our understanding of the space environment improved, new and more reliable technologies became available, and a wealth of lessons learned educated us [1][2]. Lessons from the past continue to drive new ways to make Faster-Better-Cheaper (FBC) missions, including using Commercial-off-the-Shelf (CotS) components, frequent and early testing, and concurrent engineering methods. The demand for FBC space projects provides research opportunities, one that the University of Manitoba Space Technology and Advanced Research (STAR) Laboratory continues to pursue [3].

With the advent of nanosatellites, space has become more accessible to the public. Their low cost of production and compact nature provides a fertile ground for the study of space systems. Many initiatives take advantage of the low cost of CubeSats, enabling more hands-on training for future Highly Qualified Personnel (HQP) [4][5]. There is existing research in the application of the traditional initiation, planning, execution, control and closure approach. While CubeSat teams do not have the same amount of resources as big space missions, small teams allow them to be more adaptable and capable of taking lessons from other industries that have experimented with Agile Philosophy, Concurrent Engineering, Lean Manufacturing, and Theory of Constraints.

The STAR Laboratory have been selected to participate in the Canadian CubeSat Project (CCP), and we are taking this opportunity to find ways to improve space missions [6]. We are excited to share project management methods and tools we are incorporating into our ManitobaSat-1 mission.

3 Keys to Failure

Workflow is important for keeping a project on track. It is easy to spot blocks or starvation when work is visible, as is the case for construction sites or assembly lines. Invisible work is just as vulnerable to delays, but harder to evaluate, making it more difficult to address promptly.

Playbook [7], a lean-agile visual work management process for hardware projects, has identified four common causes of delays for invisible work:

1. **Incorrect Priorities**
   Every day the critical path task is not worked on, the project gets one day longer. This might not seem very significant at first, but if you only work on the correct priority half the time, the length of the project will double! And if people have more than a few tasks to choose from, and they can't see the impact of their decisions, there's a good chance they won't choose correctly even half of the time.

2. **Multitasking**
   A common reaction to not having clear priorities is to multitask. The myth of multitasking says that if we work on two tasks at the same time, we can get more work done in the same amount of time. The reality is that attempting to focus on multiple tasks at once slows progress on both tasks, increasing overall work time of both tasks rather than reducing it

3. **Unavailable Resources**
   It's very common these days to have too much work-in-process (WIP) in the system. This increases the capacity loading of the resources, which has the detrimental effect of reducing their available time to work on any one thing. This creates a queue where the work sits idle and waits to be worked on. As before, every day the critical path task isn't worked on, the project completion date is delayed another day.

4. **Technical Difficulties** Projects with high amounts of risk (like aerospace) are often delayed due to technical issues. These can be single events that cause delays that range from a few days to weeks or even months. Fortunately, because these are so common, there are now robust and well-defined risk management processes that were designed to identify and mitigate these types of risks long before they make an impact. However, it is necessary to account for this risk management time when building the project plan so that the team members are allotted the time to get it done.

All four items will cause delays, but items 1-3 are more frequently overlooked, and can have the biggest impact because the daily slips are not noticed.

4 What Tools are Available?

Incorporating practices from modern management philosophies can provide nanosatellite teams with new tools and insights to improve the workflow of their missions. The following sections detail tools and methods to reduce the three controllable causes of delays:

4.1 Systems Engineering

Space missions are driven by their requirements, providing guidance on the important spacecraft functions and expected environments. CubeSat development teams need to ensure that all stakeholders understand the mission requirements. One of the most powerful tools available to manage requirements is a system engineer.

NASA [9] defines systems engineering as "a methodical, multi-disciplinary approach for the design, realization, technical management, operations, and retirement of a system." A systems engineer is a central part of a space project, they take information from stakeholders, identifying their objectives, wants, and needs. This information is then adapted to form a set of requirements that will act as the road map for the nanosatellite. System engineers are responsible for coordinating requirements through all the subsystems and ensuring that inter-subsystem interfaces function as intended.

The systems engineer is a common tool and resource used by the space industry, ensuring that all members have clear priorities. A system engineer needs to be knowledgeable in different and varied disciplines, and be able to communicate clearly and effectively.

4.2 Agile Philosophy

In 2001, the Agile Manifesto initiated a multidisciplinary interest in software development's ability to quickly adapt to change. The manifesto describes four core values that dictate how software development should focus their efforts:

1. Individuals and interactions over processes and tools
2. Working software over comprehensive documentation
3. Customer collaboration over contract negotiation
4. Responding to change over following a plan [10]

The Agile Philosophy provides guidance in bringing value to the customer as quickly as possible while adapting to any changes through the project lifetime. Each value provides recommendations in decision making, guiding development teams in ways to improve workflow. The first value believed that the team is the center piece of any project; if the team is dysfunctional, there will be no tools or procedures that can replace strong teamwork. The second value argues that the customer will find presentable product more valuable than documentation. Creating information for the customer is important, but it should not replace the design and construction of the product. The third claims working with the customer instead of arguing the details of a contract. If the customer is not constantly involved in the design, the project is at risk of doing rework when project visions clash. Involving the customer early will give a more unified vision of product requirements and definitions. The last value claims to respond to change over following a plan. Creating a project plan is important, it provides clear priorities and highlights expected work for each resource. When the unexpected occurs, it is important for the team to be able to respond to changes and correct any new non-conformances. This value doesn't say to abandon the plan, but update the plan with the new project landscape.

These four values can be summarized as teamwork, workflow, communication, and adaptability. Being able to respond to change is dependent not only on a project's ability to adapt, but also on the capability of the project's infrastructure to enable change. There is no one true praxis of the Agile Philosophy as every project is different, meaning different tools will work for different projects. However, there are some tools and methods companies have identified that have provided value to a variety of projects.

One common application of the Agile Philosophy is the scrum approach, which has been the subject of academic interest regarding its impact in industry. Petrini and Muniz [11] describe the scrum as a holistic approach that increases speed and flexibility of project tasks, focusing on the work to be completed within a time window. At the beginning and end of each window, the team will have a better understanding of the health of the project, evaluating if work needs to be amended or abandoned to meet deadlines.

A detailed work plan is created at the beginning of each time window, highlighting task priorities, establishing roles and responsibilities and updating the project plan based on the work previously completed. Once work begins, development teams hold very short daily meetings to communicate what work has been completed, what will be done, and if there are any blockages for tasks. This informs all working team members of critical work, preventing slippages caused by incorrect priorities.

A similar tool that can improve the adaptability of a project plan is to adopt a rolling wave planning method [12]. It begins with the creation of a high-level plan, from project initiation to closure, that outlines a summary of tasks. The manager then provides the sub-system managers ownership of the summary tasks, allowing them to fill in the details, including work descriptions, expected duration, and required resources. Similar to Scrum, summary task owners will plan for a certain time window, but rolling wave differs by planning in detail to the next project milestone. The rolling wave plan is assessed by every owner every one or two weeks. This ensures that the plan is constantly updated, incorporating any unexpected change, or rework.

Space missions are able to incorporate the body of knowledge developed by the diverse industries seeking to make agile projects. The ability to quickly adapt to changes is especially valuable after major project reviews where the customer is able to easily and freely communicate with the development team regarding their vision.

4.3 Concurrent Engineering

Concurrent Engineering is defined by Doerksen and Klooster [13] as "a system design practice that encourages immediate collaboration between groups working on interrelated subsystems." Concurrent Engineering aims to involve all stakeholders at the beginning of the project so that their input can be incorporated early when there is time and flexibility to do so. The most common example is having the manufacturing engineers involved in writing requirements and the early design phases so that design-for-manufacturability features are considered from the start. This operation is similar to an assembly line with parallel work paths that come together to make a working part. This can be a powerful management approach, allowing many interconnected parts of a project to be completed simultaneously.

The core of Concurrent Engineering is decentralizing communication, improving the team's ability to transfer knowledge. This promotes multidisciplinary cross-training and awareness of system interactions which provide team members with a better understanding of how decisions will affect other sub-systems. The project manager role changes from control to guidance.

Concurrent Engineering is a proven tool in the space industry, ensuring that all priorities are clear. The real strength of Concurrent Engineering is the decentralized communication, allowing various subsystems to clearly state their focuses and values.

4.4 Lean Manufacturing

Lean manufacturing was developed by studying the Toyota Production System which focuses on the workflow. Many companies seek to improve profits by cutting costs, but the Toyota engineer team saw cost cutting as a long term handicap in production. Toyota engineers instead focused on improving operations workflow, reducing the time to market, seeing instead a cost of delay. Reinertsen [13] brings forward many concepts that provide stable work throughput, including mindfulness to work queues and resource capacity. Queues can be defined by two factors: queue or waiting time, and service time. Whenever a resource is used, it builds up a queue of work. The more tasks are expected of the resource, the longer it takes for it to complete all required work. Although this concept seems simple, it can also be misleading, as the amount of time work is in a queue has a non-linear relationship with the workload on the resource. For example, at 80% loading, a 10% increase in work will almost double the cycle time for that resource..

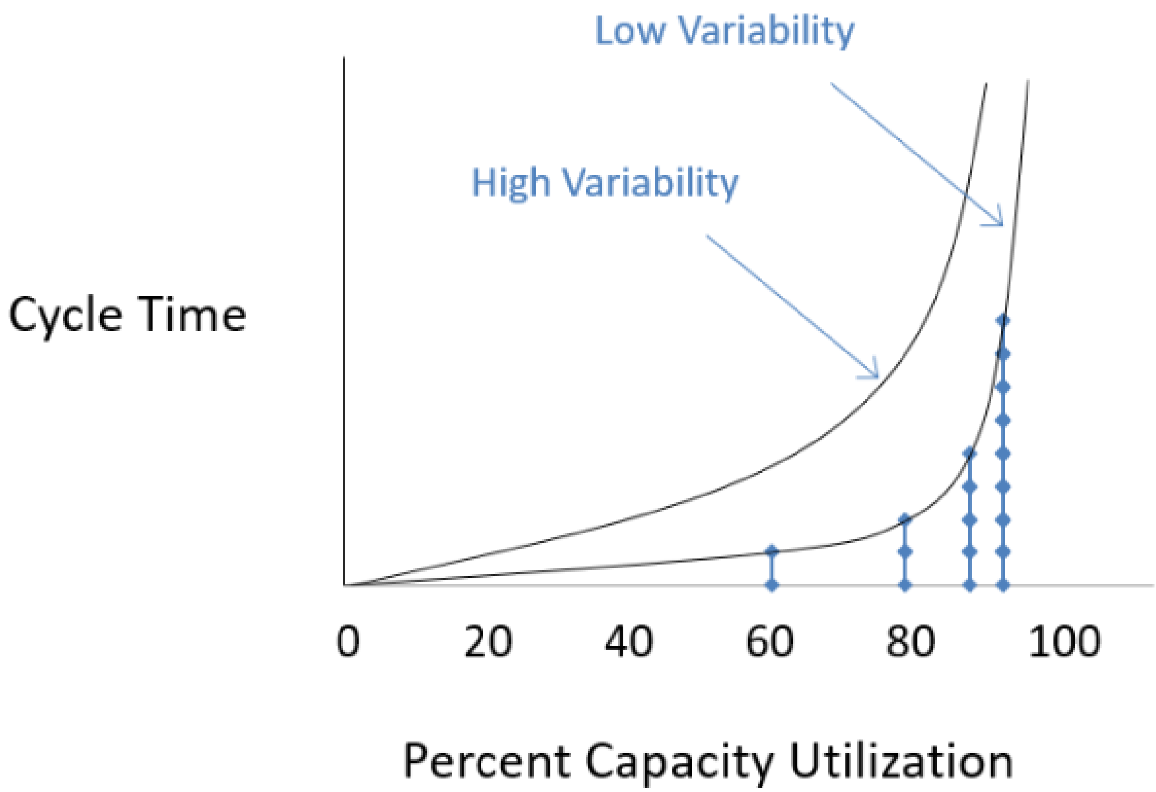

Figure 1: Cycle Time vs Percent Capacity Utilization [7]

You can see in the graph above, that when the system is at 60% capacity utilization, new incoming work will have a given cycle time. (It could be one minute, one hour, one month, etc.) However, if you increase the capacity loading by half of the remaining amount between where you measured and 100% (20% in this case), the cycle time at that new state (80%) will double. And this phenomenon continues. For example, the cycle time at 90% utilization is twice as high as the cycle time at 80% utilization. And it doubles again when you move from 90% to 95%. This is the reason that manufacturing never runs their plants at capacity loadings higher than 80 or 85%. Also notice that in systems with high variability (like engineering compared to production) your cycle time is already much higher at lower levels of capacity loading.

Capacity can be defined in many different ways. For example, an oven's capacity is defined by the amount of space inside. For designers, it boils down to the amount of time in a day. It is crucial for managers to be mindful of the workload of all their resources to ensure that delays do not occur from overloaded resources. To assist with monitoring work loads, another tool used in Lean manufacturing is the Kanban system. This creates a pull (vs push) system and reduces resource loading and inventory.

The word Kanban translates to "card" or "signboard" in Japanese, and it is a workflow system that continues to bring value to many hardware and software companies [14]. The Kanban system in manufacturing is created by placing two carts between two work cells with a card in it that says how many pieces of finished work can go in the cart. Each cell has an incoming cart with work pieces that need to be worked on, and an outgoing cart in which to put the finished work. When the finished work cart is full, it is moved to the next cell. If there is no incoming cart with work in it, the operator has to wait until one arrives. Similarly, if there is no outgoing cart in which to put the finished work, you have to stop working and wait for an empty cart to come back from the downstream process. This simple process has the ability to not only load the system at the desired level, it also prevents queues from developing that are larger than the number on any card and instantly stops the entire flow of work if one cell gets blocked for any reason. Although at first glance this appears as a problem, it provides the system with a built-in warning. If one cell is blocked, the stoppage of work immediately alerts adjacent cells that they can, and should, go to help the blocked cell so it is fixed as soon as possible. And in the case where the cell is blocked because it is receiving defective work from upstream, it prevents the error from being repeated again on a large batch of work. [14].

Manufacturing is not the only environment where Kanban has been used. Software developers have created a similar system that they use to supplement the Scrum approach that has many of the same benefits and is also called Kanban. Since they are not moving around physical parts, they use a board with cards on it that represent the features or "stories" they are working on. The board has a series of columns progressing from left to right that represent the "phase" or lifecycle that each story has to go through in order to be released. A simple example might be Backlog, Development, Testing, and Done. Each story is represented on a card (usually a sticky note) that is moved to the next column when the current work phase has been completed. This has many benefits. First of all, since you can limit the number of cards you let onto the board, you effectively limit the WIP, which prevents the overloading of resources. It also makes the work visible, which allows you to identify blockages or starved resources. So, if you see a pile of cards in the Testing phase, you know that resource is blocked and needs some help. By allowing each person to only work on one card at a time, it prevents multitasking.

Lean manufacturing has continuously improved each tool, finding success not only in the automobile industry, but many others. The space industry can take advantage of the focus it provides designers and operators, providing a stable workflow.

4.4.1 Theory of Constraints

Theory of Constraints (TOC) was originally proposed by Eliyahu Goldratt in his book The Goal [16]. TOC searches through a system to find bottlenecks that can either starve downstream work or block upstream work. To find bottlenecks and improve the workflow, TOC suggests five steps:

1. Identify a system's constraints
2. Decide how to exploit constraints
3. Subordinate everything to the above decision
4. Alleviate the system constraints
5. If previous steps' constraints have been broken, start at step 1, but don't allow inertia to be a system's constraints

TOC was created for manufacturing, but it also developed an application for project management called the Critical Chain scheduling method [16]. Critical Chain uses traditional schedule building methods with a few additions, creating a project buffer and incorporating resource loading into the schedule. First, all of the "buffer", or padding, is taken out of the individual work duration estimates. Then all of the work is load leveled for each resource so that a single resource is not working on multiple tasks at the same time. Then, a buffer is created at the end of the project to account for all of the padding that was taken out of the individual task estimate.

Robinson and Richards [18] views the removing of the buffers for individual tasks as a useful approach, as procrastination is a powerful force. Also called the student syndrome, when compounded with other urgent tasks, it is not uncommon for operators to allow time to pass without completing the work.

Removing the padding from the tasks encourages the resources to focus. Load leveling the resources creates a more realistic schedule. Finally, the project buffer accounts for the variability that will occur when completing the work so the schedule is not only more accurate to begin with, but work is completed with a sense of focus that prevents delays.

Space projects are a complex and multi-disciplinary effort with many contributing resources. TOC assists the space industry in identifying and managing bottlenecks and overloaded resources, providing management with valuable information when decisions need to be made.

4.4.2 What About Risks?

Risks are one of the most important elements of space projects. NASA [19] defines risks as "the potential for performance shortfalls, which may be realized in the future, with respect to achieving explicitly established and stated performance requirements." It is important for projects to meet the established requirements, every potential situation that can cause requirement non-compliance needs to be mitigated.

When mission requirements are created, a baseline risk registry that documents all risks that will affect the satellite's ability to meet requirements should be created as well. NASA recommends using the following risk categories: safety, technical, cost, or schedule. Important information for characterizing each risk includes the scenario, likelihood of the scenario, and the consequence of the risk being realized. NASA's Risk Management method consists of two parts: Risk Informed Decision Making (RIDM) and Continuous Risk Management (CRM). RIDM explores project decisions and possible alternatives, measuring the level of risk involved and performance measurements. CRM takes the decisions made in the RIDM process and characterizes risks using scenario, likelihood, and consequence, defined as:

- The scenario(s) leading to degraded performance with respect to one or more performance measures (e.g., scenarios leading to injury, fatality, destruction of key assets; scenarios leading to exceedance of mass limits; scenarios leading to cost overruns; scenarios leading to schedule slippage).
- The likelihood(s) (qualitative or quantitative) of those scenarios.
- The consequence(s) (qualitative or quantitative severity of the performance degradation) that would result if those scenarios were to occur [19]. Whenever there are key decisions to be made during the project, the RIDM process is started, using information maintained by the CRM. This process iterates until the project close-out.

Once the risk has been identified, a response plan to the risk should be developed. A proactive approach for high severity risks can be incorporated into the project schedule. The Agile Philosophy will incorporate all risk response strategies and include them in a Scrum planning period.

Space is a dangerous environment, having many different risks that could fail any mission. The space industry provides many lessons in understanding the dangers of the environment, shortcomings of the available technology, and finding the best way forward.

5 Closing Remarks

The ManitobaSat-1 team is made up of students of various academic backgrounds with varied experience. In our pursuit of creating a successful mission, we continue to find management philosophies, methods, and tools to improve our work throughput. Large space missions have shown success, methodically documenting their successes, failures, and ideas to improve in the future. Nanosatellite projects are different from large space projects, but we believe that methods and wisdom from industry can provide strong guidance. Tools presented in this paper provide approaches that we have found have brought value to our CubeSat project by improving communication, ability to adapt and test changes, and identify possible opportunities and dangers.

6 Acknowledgements

The ManitobaSat-1 team would like to thank the Natural Sciences and Engineering Research Council (NSERC), the Canadian Space Agency (CSA), and Magellan Aerospace for supporting this research. The author would also like to thank Accuer, the developers of Playbook, for providing information and guidance in the many philosophies and tools in project management methods.

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