SYSTEM DYNAMIC MODELING OF COST AND SCHEDULE PERFORMANCE OF SPACE PROJECTS

ABSTRACT

Like complex projects in other sectors, space projects frequently exceed cost and schedule performance targets. Reasons frequently cited for this include excessive optimism at the start of projects, political interference, technology development challenges such as design flaws and rework, changes to the work content during the project, and integration issues. Problems with progress can rarely be isolated to just one aspect of a project or system, however, and decisions taken in one part of a project to remedy a perceived problem may have unanticipated consequences later, elsewhere in the project. Based on data from a space science institute, this research presents a model of project progress to understand the effectiveness of the strategies available to managers of complex instrumentation projects. The paper focuses on the decision making around staffing when progress falls behind schedule and finds that practical challenges in expanding capacity in a team may mean that schedule slippages experienced early in the project lifecycle are unlikely ever to be reversed, even if additional resources are made available. This reinforces the importance of comprehensive risk analysis, thorough cost and schedule estimating at the start of the project, and the availability of realistic funding from the outset.

Keywords: Space project management, system dynamics, rework

1. INTRODUCTION

1.1 BACKGROUND

1.1.1 PERFORMANCE OF SPACE SECTOR PROJECTS

The global space industry has grown at an average of over 8% per year in the last five years, increasing from $256 billion in 2013 to $383 billion in 2018 (OECD 2014; Space Foundation 2018). At the same time, new visions for exploration have emerged from global space agencies, such as ESA's moon village (Casini et al. 2018; Lehner et al. 2019; Maccone 2019; Madhavan Nair, Sridhara Murthi, and Prasad 2008; Marboe 2019; Sherwood 2017, 2019), NASA's Lunar Orbital Platform (Burns et al. 2019; Sherwood 2017) and the prospects of manned missions to Mars (Burns et al. 2019; Casini et al. 2018; Madhavan Nair, Sridhara Murthi, and Prasad 2008;

Sherwood 2017; Shishko et al. 2017; Woolley et al. 2019). To support these ambitious initiatives, NASA plans to invest around $63 billion over the lifecycle of its current portfolio of 24 major projects (each having a base budget of at least $250 million) (Government Accountability Office 2019).

Space projects continue to encounter cost and schedule overruns, however (RAND Corporation 2015). Cost and schedule performance at ESA has not improved significantly over the last few years despite their recognition of the need for "implementation of measures to better control projects' costs and planning"(ESA Ministerial Council 2008; European Space Agency 2017). Projects at NASA are also consistently delivered late and over budget, with an average of 27.6% cost overrun and 13 months of schedule delay (Government Accountability Office 2019). Cost increases are strongly correlated with schedule increases. A study of 20 NASA projects found that schedule growth from the start of the 'definition phase' (phase B) could explain 62% of the variability in project cost growth (Majerowicz and Shinn 2016).

A poor performance against budget and schedule is not unique to the space sector. A survey from Proctor and Gamble found that 15% of projects have a 50% cost overrun relative to the original budget (Scott-Young and Samson 2008), and US government data from 20 large infrastructure projects revealed a budget overrun from 40% to 400% (Hecker 2002). These delays and increases in cost can lead to billion-dollar lawsuits (Callahan, Bramble, and Lurie 1990) and can even affect national politics (Pear, Lafraniere, and Austen 2013).

1.1.2 CAUSES OF COST INCREASES AND DELAYS

The success of modern organizations relies on the successes of their projects to implement new technology and processes, as a way of addressing increasing innovation within the supply chain and managing the constant pressure from stakeholders to reduce time to market (Gunasekaran and Ngai 2011). As the market demands solutions to increasingly difficult problems, companies are forced to implement new methods and frameworks to produce their products within time and cost constraints. As system and project complexity increases, so does the level of challenge (Chen, Reilly, and Lynn 2012; Griffin 1997). In this context, it is important to understand the project's success factors (Tsiga, Emes, and Smith 2016b, 2016a, 2017), to explore the links between these factors, and to conduct a comprehensive assessment of a project's risks. The design and development stages of projects are critical in the aerospace sector; delivering them on time and on budget strongly influences success or failure (Reichelt and Lyneis 1999).

At a hearing before the US House of Representatives, the NASA Inspector General suggested that major causes of cost and schedule overruns in NASA projects were often managerial or political rather than technical (US House Subcommittee on Space 2018). The following key contributing factors were cited:

1. Culture of optimism, including three main aspects: (i) measures of project success do not include cost and schedule factors, (ii) establishment of unrealistic cost and schedule baselines, and (iii) an expectation that additional funding will be made available if a project runs into difficulties
2. Underestimating technical complexity
3. Funding instability
4. Development and retention of experienced project managers

These factors echo previous findings from Europe. 30 major projects were reviewed by ESA following the instruction by ESA's Council of Ministers to "put in place methods, processes and tools to reinforce the Agency's capabilities to control the cost and planning of ESA projects" (ESA Ministerial Council 2008). The ESA Inspector General noted that (in the 'Edwards report') 14 generic causes of cost and schedule slippage had been identified. Foremost amongst these, a 'conspiracy of optimism' was noted as the greatest cause of cost and schedule slippage, with insufficient design maturity, optimistic initial cost estimate or cost allocation for subcontractors, optimistic initial schedule estimates, programmatic imposition, and insufficiently demonstrated technology as key avoidable causes of overrun linked to the initial decision to undertake the project (European Space Agency 2017).

Delays encountered in overcoming technical challenges also clearly play a part, and problems are exacerbated when work has to be repeated to correct latent defects. According to Parchami (Parchami Jalal and Shoar 2017), such labor (and consultant workforce) 'rework' was among the most important factors influencing delay in construction projects. A report investigating cost performance for 433 US Department of Defense (DoD) projects in the period 1970 to 2011 concluded that 55% of cost increases could be explained by work content changes, with 45% due to costs exceeding targets (due to unrealized assumptions, external factors such as higher materials costs or poor contractor performance). Work content changes may be due to planned additional work options that are exercised, changes to system specification, unanticipated engineering changes needed in order to meet requirements, change in quantity, poor understanding of technical maturity, changes to requirements or poor contractor performance

(OUSD AT&L 2013). When examining 37 space projects specifically, however, it was found that work content changes were responsible for only 40% of cost growth, whereas cost over target explained 60% (Figure 1).

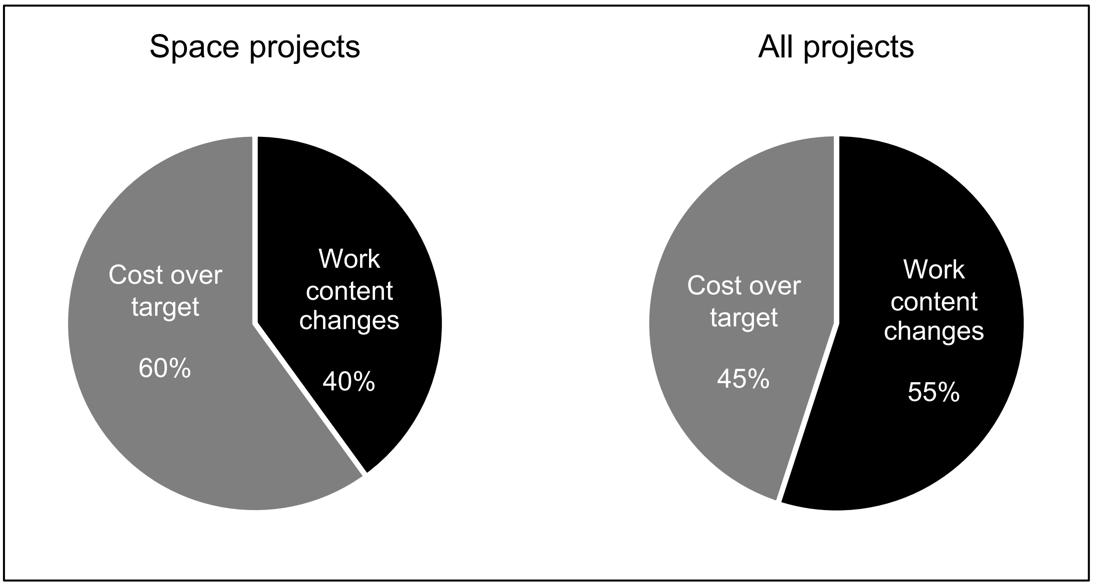

FIGURE 1: CAUSES OF COST GROWTH IN US DEPARTMENT OF DEFENSE (DOD) PROJECTS (OUSD AT&L 2013)

The same study examined six space projects in detail to determine the causes of cost increases (Table 1) and found that, for this set, only 25% of cost increases were due to work content changes. Rework was the single largest contributing factor overall (contributing at least 27%, but arguably as much as 46% when design flaws and design changes were seen as part of rework).

Factor	Share of cost change
Work content changes	25%
New sub-tier requirements	8%
Additional testing	14%
Requirements clarification	4%
Requirements descope	-2%
Key performance parameter changes	0%
Cost over target	75%
Technology development	18%
Delays/rework	13%
Engineering studies	2%
Additional testing	2%

Design changes	1%
Integration	23%
Payload	8%
Vehicle	7%
Command/control	7%
Contractor execution	34%
Rework	14%
Design flaws	18%
Obsolescence	1%
Supplier delays	1%

TABLE 1: FACTORS LEADING TO GROWTH IN SPACE PROJECT COSTS (OUSD AT&L 2013)

1.1.3 REWORK

The concept of rework generally refers to the task or activities that must be done to fix defects, quality deviations or functional failures, in order to deliver a level of performance necessary to comply with the stated requirements (Lyneis and Ford 2007). Rework can also be defined as the repetition of an activity or process because it has been executed incorrectly in the first instance (Peter E. D. Love 2002). The design process can also be affected by rework, when a failure in design, poor communication or an unclear requirement may affect the efficient transfer from user to system requirements. (Peter E. D. Love and Smith 2003). Thus, design errors or late changes may be included in rework studies, even where system defects are not manifest (Mills, Love, and Williams 2009).

Several research projects have studied rework, mostly in the construction industry. There have been rather few (qualitative or quantitative) models published that explain its dynamic behavior, however (Sommerville 2007), perhaps due to a lack of systems to monitor and control the progress of projects and capture the data relevant to rework (Hwang et al. 2009). Rather than a subject for study and optimization in projects, rework is often seen as immutable, and its cost has been found to be substantial (Peter E.D. Love et al. 2014; Moore 2012). Rework fuels both cost and schedule growth in complex projects, and there is a strong correlation between rework and schedule overrun (P. E D Love et al. 2002). Nonetheless, rework can be obfuscated behind project data, as managers can deal with it by using concurrent engineering or moving resources that would otherwise be committed to another task, thus increasing the cost of the project (P. E D Love et al. 2002). Whilst there is substantial research on the impact of rework in infrastructure projects, there is very limited literature regarding rework in the space sector. One exception is when Owens *et al.* (Owens, Leveson, and Hoffman 2011), researched the rework carried in the flight communication procedure inside space shuttle mission control, finding that rework mostly appears when a method has an inconsistency that will not lead to an accident unless other conditions are present at the time the problem arises (Owens, Leveson, and Hoffman 2011). Even if the procedure is flawless, however, there is still a margin for error and rework when the process must be executed under time pressure.

1.1.4 ATTEMPTS AT IMPROVEMENTS

With all major public investment comes scrutiny and concern for value for money. Governments, space agencies and private businesses have therefore shown significant interest since the end of the space race in reducing the cost of access to space, whether for large scale scientific activities such as NASA attempted through the Faster, Better, Cheaper initiative in the 1990s (McCurdy 2003) or for smaller-scale space tourism (Chang and Chern 2016; Sherwood 2017). The RAND Corporation has issued guidance on good practice for estimating space systems, noting the extreme challenges of estimating the costs of space systems (Fox, Brancato, and Alkire 2008). They offer several explanations for the difficulty, including the high cost of failure, the harsh physical environment, the low- volume/customized production context, and the fact that components are tightly integrated and tightly coupled so that problems propagate easily from one part of the system to another, a point also raised by Perrow (1999).

Since 2006, NASA has implemented a number of initiatives to improve baseline estimating and monitoring of progress, with earned value used for the latter (Kwak and Anbari 2012). Since 2009, NASA has used a formal process called Joint Cost and Schedule Confidence Level (JCL) on all major projects (above $250 million). This approach calculates the percentage likelihood that the project will be developed at a given cost and schedule, with projects generally funded at the 50 percent confidence level and budgeted for at the 70% confidence level (NASA Office of Inspector General 2018).

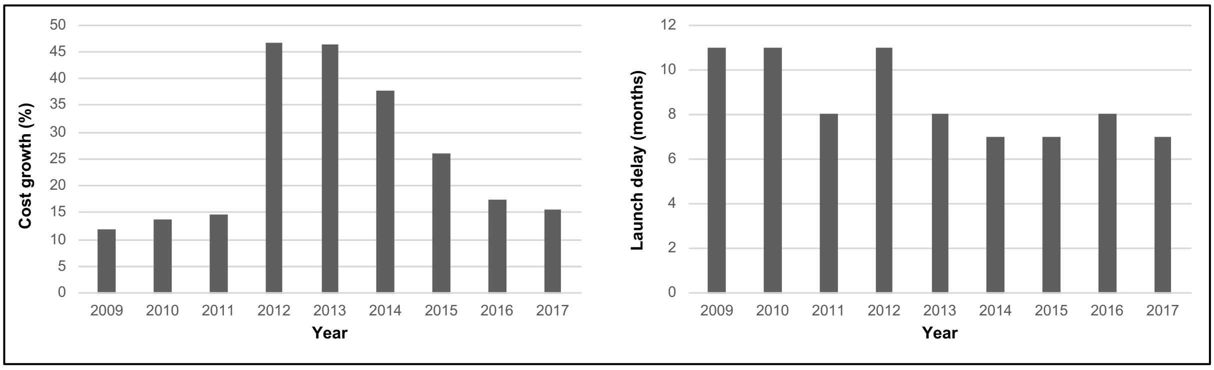

FIGURE 2: COST AND SCHEDULE PERFORMANCE OF NASA PROJECTS (GAO 2017)

In addition, NASA has given considerable scrutiny to its choice of contracting mechanisms, recognizing that "properly structured and executed, incentive contracts can reduce the risk of cost overruns, delays, and performance failures by providing a well-performing contractor the opportunity to earn additional money" (*ibid*). International partnerships are increasingly utilized as a way of sharing the costs and risks of undertaking major programs (especially for exploration beyond low Earth orbit). Public-private partnerships, in particular exploiting the capabilities of NewSpace organizations (Denis et al. 2020; European Space Agency 2016; Sherwood 2017), are also being used to share financial risk with private industry. Collaborations come with coordination challenges, however, and some joint programs experience significant cost growth, especially where institutions seek to retain autonomy (Dwyer et al. 2018). Nevertheless, since these initiatives have been introduced, NASA has seen a significant improvement in the cost and schedule performance of its major projects, as shown in Figure 2.

Improvements in cost and schedule performance of space projects may also be achieved through technological improvements. ESA's technology strategy notes that the space sector is in a period of fundamental change where new commercial opportunities will be met through the digital transformation of engineering, based around lower cost and shorter, agile development cycles. These are expected to enable 30% faster adoption of innovative technology and a 30% improvement of spacecraft development time by 2023, with an order of magnitude improvement of cost efficiency with every generation (European Space Agency 2018).

1.2 OBJECTIVES

Although various reports at the procurement agency level have identified causes of cost and schedule overrun in the space sector and identified some strategies for improvement (as discussed in section 1.1.2), there is limited understanding of how cost and schedule challenges manifest through the supply chain. The research reported in this paper is part of a doctoral research study that models a spacecraft subsystem supplier's cost and schedule performance. Any model will necessarily be a simplification of reality and will therefore need to be selective about which variables are included (John D. Sterman 2002). This paper focuses on modeling the impact of unanticipated tasks that arise due to rework, design changes and the emergence of unplanned tasks due to project complexity, since these factors were identified as major challenges for contractors. The model is used to explore how an organization responsible for the delivery of a key instrument or subsystem for a major international space mission can control cost and schedule performance through its staffing decisions.

This paper is structured as follows. In the next section, the research methods are introduced. This is followed by the results of the modeling, a discussion of the implications in the context of the literature and the original objectives, and finally the conclusions are presented.

2 METHODS

2.1 IDENTIFYING CAUSES OF PROBLEMS IN SPACE PROJECTS

The study employs a sequential exploratory research design (Creswell 2014) based upon a case study of rework and workforce management strategies for programs undertaken by a leading space subsystem supplier. From the literature, 198 factors were identified that influence rework within projects, mostly derived from the construction sector. To ensure that the qualitative data was not biased by the authors' own experiences (Wu 2009), a meeting was held with project specialists at a space science institute to qualify the importance of the factors that were selected from the literature review, with the question posed: "For each of the following factors, please indicate the extent to which you agree that the factor is a cause of problems in your projects". A five-point Likert scale was used to capture responses, with the options 'Strongly Disagree', 'Disagree', 'Neither Agree nor Disagree', 'Agree', and 'Strongly Agree'. This enabled a set of critical rework factors to be identified.

2.2 SYSTEM DYNAMIC MODELING OF PROJECT PERFORMANCE

Systems dynamics is a modeling technique used to understand and study the dynamic and complex behavior of systems using a numerical data and transfer into a graphical expression of the results (J. W. Forrester 1997; Ghosh 2017; Meier and Boßlau 2013; Morecroft 2015; J D Sterman and Bayer 2000). System dynamic modeling identifies non-obvious system-level performance emerging over time from the interaction between the system's elements. Delays often make the consequences of interventions intended to improve system performance difficult to anticipate. It was first developed in the Sloan School of Business at the Massachusetts Institute of Technology (MIT) by Jay W. Forrester while working simulations, feedback control engineering and understanding the difficulties that business was facing and how the complexity of business is harder to simulate than a physical or engineered system (J. W. Forrester 1997). Non-engineering systems, such as socioeconomic processes and projects, are frequently represented by causal loop diagrams (Ghosh 2017). After identifying the common causes of problems as outlined in section 2.1, the causal connections between them were determined, with causal loop diagrams used to show the influences between variables and the polarity of the links (J D Sterman and Bayer 2000); these diagrams were reviewed at the space science institute to ensure that the causality was well represented in the model. The causal loop diagrams were developed into stock and flow models to capture the dynamic complexity of the system and to simulate quantitatively how the levels of variables changed over time. Stocks represent the accumulation or integration of flows, and a stock as a function of time, *S(t)*, can in general be written (Equation 2):

$$S(t) = \int_0^t \big(Inflows(t) - Outflows(t)\big)\, dt$$

EQUATION 1: STOCKS AS INTEGRAL OF FLOWS

Equivalently, the rate of change of stocks $\frac{dS}{dt}$ is simply equal to the net inflow, or the difference between the total of all inflows at time t and the total of all outflows. Stock and flow models are built from a diagram showing the network of stocks (shown as rectangles) and the flows between them shown (depicted as valves on the connectors between the stocks), with initial values of stocks and equations governing the flows specified. These models then operate like ‘management flight simulators’ (Keith, Naumov, and Sterman 2017), enabling us to set up ‘what-if’ scenarios, examine changes in system behavior and explore the effectiveness of various possible interventions to a system (H N Le, Wynn, and Clarkson 2010). Basic models of rework (K. Cooper 1994; K. G. Cooper and Mullen 1993; Reichelt and Lyneis 1999) were expanded to incorporate the problem factors identified in the causal loop diagram, and to capture the complex behavior of the execution of tasks within the project, including hiring, training and motivation factors, for example.

The preliminary stock and flow model that was generated was compared with 21 models from the literature that studied rework (mostly within the construction industry), and iterated to produce a model that was ultimately felt to be a good reflection of the types of challenges faced by projects in general, whilst sensitive to the particular circumstances of the space science institute. Over thirty simulations were carried out in order to set the initial values of the parameters in the model, to check the underlying equations and to ensure that the system behavior reflected the observed performance in real projects. The model was then used to investigate two major staffing options available to project managers seeking to control cost and schedule performance in the face of additional tasks: (i) to recruit additional engineering staff, and (ii) to extend the number of working hours per week (the ‘workweek’) by asking engineering staff to perform overtime.

2.2.1 Recruitment of additional engineering staff

The model explored the cost and schedule implication of the parameters or constraints affecting the recruitment of engineering staff.

- Constraints on the maximum staff uplift possible through recruitment when under schedule pressure (0%, 50%, 100%, 400%)
- Delay in completing the hiring process, from a need identified to establishing new staff in a post (30 days, 60 days, 90 days or 120 days).

The budget for a project will have been determined in advance, with funding provided for a specified level of staffing. Whilst funds will typically allow for the replacement of any staff that leave during the project, there will be very limited resources available to recruit additional staff should these prove to be needed. Given the high importance of the international space projects to which the space science institute contributes, however, and the possibility for reputational damage if schedule performance is poor, the model has examined the overall cost and schedule impacts of allowing an increase in staffing when this is required.

Recruitment of new permanent staff is typically a lengthy process, partly due to the process of obtaining authorization from various parties in the hierarchy of the space science institute, and partly due to the process of advertising for staff, interviewing and then agreeing on a start date sensitive to any existing commitments of the new employee. Given that staff used are a mix of permanent staff and contractors, the average recruitment delay could reasonably be anywhere in the range of 30 days to 120 days.

2.2.2 Engineering staff working overtime

The model explores the cost and schedule implication of the parameters or constraints affecting the overtime rules for engineering staff:

- Amount of overtime permitted: (None, 25%, 50%)
- Payment for overtime (No payment, half of overtime paid at the normal rate, all of overtime paid at the normal rate)

In practice, although contractors will typically be paid an hourly rate for all work, permanent staff will normally not be paid overtime, but will instead be given time off in lieu of overtime at a later date.

2.3 MODEL TESTING

The data entered into the model was collected from many articles on system dynamic modeling, rework, and complex project management. Although the model developed is necessarily a simplification and cannot perfectly represent reality, several validations of the inputs were made by comparing with other models in the literature (J D Sterman and Bayer 2000) to develop confidence in the model (J. Forrester and Senge 1980). Sensitivity analyses were undertaken to understand how much the model outputs changed as certain input variables were changed. This confirmed, for example, that the cost and schedule performance results were not very sensitive to the initial number of engineers on the project. The average number of tasks undertaken per day, the work quality, and the complexity of the project all had a much more significant impact on the results. Initial data for some of the generic parameters in the model (such as the schedule pressure effect on morale) was derived from past projects reported in the literature (Oliva 2003), drawing upon organizations both within and outside the space sector. Data for parameters specific to the organization such as working hours per day and salary costs were approximated in discussion with staff at the space science institute. For some key input parameters such as quality and project complexity, data was not available so values were initially assumed by the authors and then iterated after a comparison between the model's results and the past performance in real projects. The quality level, for example, was initially set at 0.8 and was increased to 0.9 as this gave a more realistic level of rework generated. Note that justifying exact values of parameters was not a major concern for this study; the principal value of the model comes from simply exploring what behavior *would* be observed for a given set of parameter values.

3 RESULTS

3.1 CAUSES OF PROJECT PROBLEMS

The literature and the interviews with project and program managers at the space science institute helped to identify 31 critical factors that cause problems in their projects, as shown in Table 2. The causal relationship between these problem factors and others deemed from the literature relevant to cost and schedule performance in space projects was developed into a causal loop diagram. For example, if the length of the workweek is allowed to increase through overtime in response to delays in the project, fatigue is caused which may even lead to a sense of "hopelessness" (Lyneis and Ford 2007). This fatigue leads to a reduction in the quality of work, which leads to an increase in errors, and ultimately undiscovered rework. A worker's productivity may be affected by many variables such as the congestion of the workspace, fatigue and also the morale of the team (Han 2008) and this is a critical variable affecting rework, since the identification of unplanned tasks has a negative impact on the morale of the workers. This will lead to an increased turnover of staff, creating a shortfall in labor, that will lead to an increase in hiring that ultimately decreases the team's overall experience and contributes to communication problems within the working teams (Fryling 2015; Keys, Baldwin, and Austin 2000). As the experience of the new workers is lower than the skilled labor, it will also mean the quality of work is again reduced, leading to more rework.

Management	**Human**	**Processes**
Project complexity	Changes in drawings	Constraint in carrying out activities
Conflicting information	Design changes	Ineffective coordination
Late changes to contract	Design errors	Difficult integration of components
Cost pressure	Errors during manufacturing	Incorrect materials procurement
Design and material changes	Insufficient experience	Procurement delays
Equipment unavailability	Lack of training	Recruitment delays
Inadequate resources	Poor teamwork	
Poor management practices	Poor work quality/workmanship	
Schedule pressure	Skill level of staff	
Shortage of staff	Unrealistic technical program	
Staff turnover	Unrealistic time durations	
Internal competition for staff	Multiplexed staff	
	Misaligned goals	

TABLE 2: COMMON CAUSES OF PROJECT PROBLEMS

3.2 SYSTEM DYNAMIC MODELING RESULTS

The basic stock and flow model for the rework cycle is shown in Figure 3. The workflow rate and error generation rate depend on the productivity of the engineers, which is influenced by various factors including schedule pressure, the proportion of experienced and inexperienced staff, fatigue, and staff morale, which in turn is influenced by schedule pressure and whether payment is received for any overtime worked.

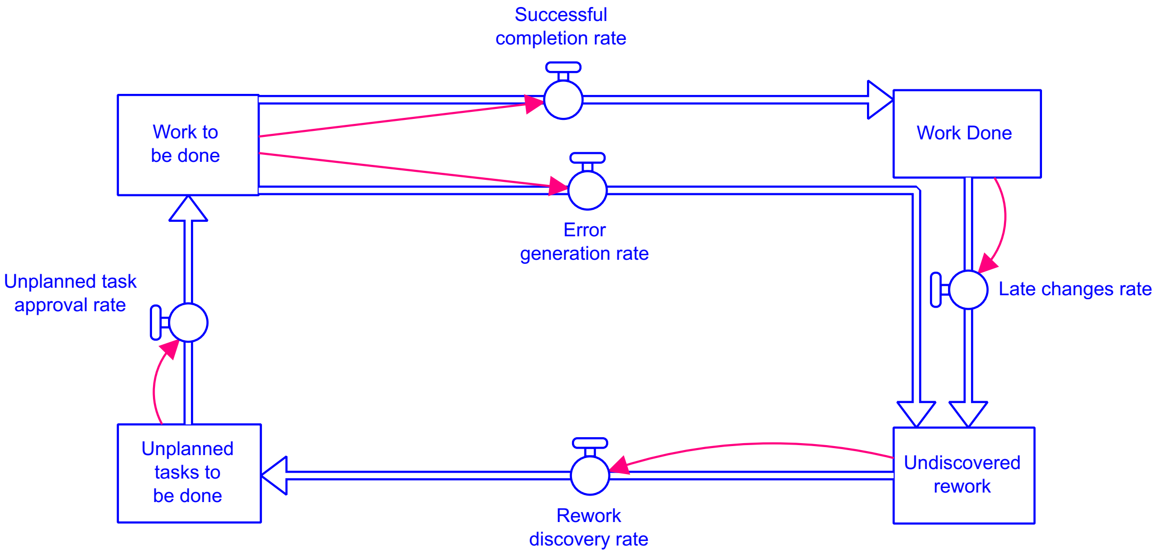

FIGURE 3 BASIC REWORK STOCK AND FLOW DIAGRAM

The project starts with 10000 tasks (‘Work to be done’) that must be completed to meet the instrument requirements as specified by the prime contractor for the spacecraft. The engineering workforce starts with ten engineers (for simplicity, the model does not differentiate between electronic, mechanical, thermal, electronic, software or other engineering specialisms), and nominal productivity of 1 task per engineer per day, giving a baseline schedule of 1000 days. Each task is assumed to require materials to the value of $50, and the base salary rate is assumed to be $150 per day; the 10,000 tasks therefore require a nominal $0.5m of materials and $1.5m in labor. The stock ‘Work to be done’ reduces through the flow of completed tasks. At the same time, due to imperfect work quality (assumed to be constant at 90%) and late changes to specifications, a stock of ‘Undiscovered rework’ begins to build up. In due course, this is discovered and added to the stock of ‘Unplanned tasks to be done’. When approved, which generally happens quite quickly, these unplanned tasks are added to the stock of ‘Work to be done’. We can express the relationship between Work to be done, $W(t)$, Successful completion rate, $S(\underline{t})$ and Error generation rate, $E(t)$, as in Equation 2. Although all work completed (both good quality work, S, and work with errors, E) initially reduces the stock of work to be done, W, the errors later lead to an increase in unplanned work, which serves to increase W.

$$W(t) = \int_0^t (U(t) - S\,(t) - E(t))\,dt$$

EQUATION 2: WORK TO BE DONE AS THE INTEGRAL OF WORK FLOWS

It is worth noting that when there is no overtime permitted and the stock of engineering staff is limited to its original level, then even with 100% work quality (so there is no rework), and when no additional changes arise due to the complexity of the project (i.e. with no unplanned tasks to be done throughout the project), the project still sees a 6.0% cost increase and a 17% schedule increase relative to the baseline. This is due to the natural turnover of staff during the project and the time lost when replacing and retraining new staff (these numbers assume minimal delay in the recruitment process itself – just 30 days between identifying the need for additional staff and having the new staff member in post). This is a significant factor (O'Connell and Kung 2007) that is frequently overlooked when estimating the cost and schedule of projects. For challenging projects the situation becomes significantly worse, as technical or other sources of complexity (Gorod et al. 2019; Maani and Cavana 2007; Remington and Pollack 2007; Sheffield, Sankaran, and Haslett 2012) can lead to significant unanticipated work in addition to any defects that occur through imperfect work quality, and any rework due to requirements changes flowing from the prime contractor.

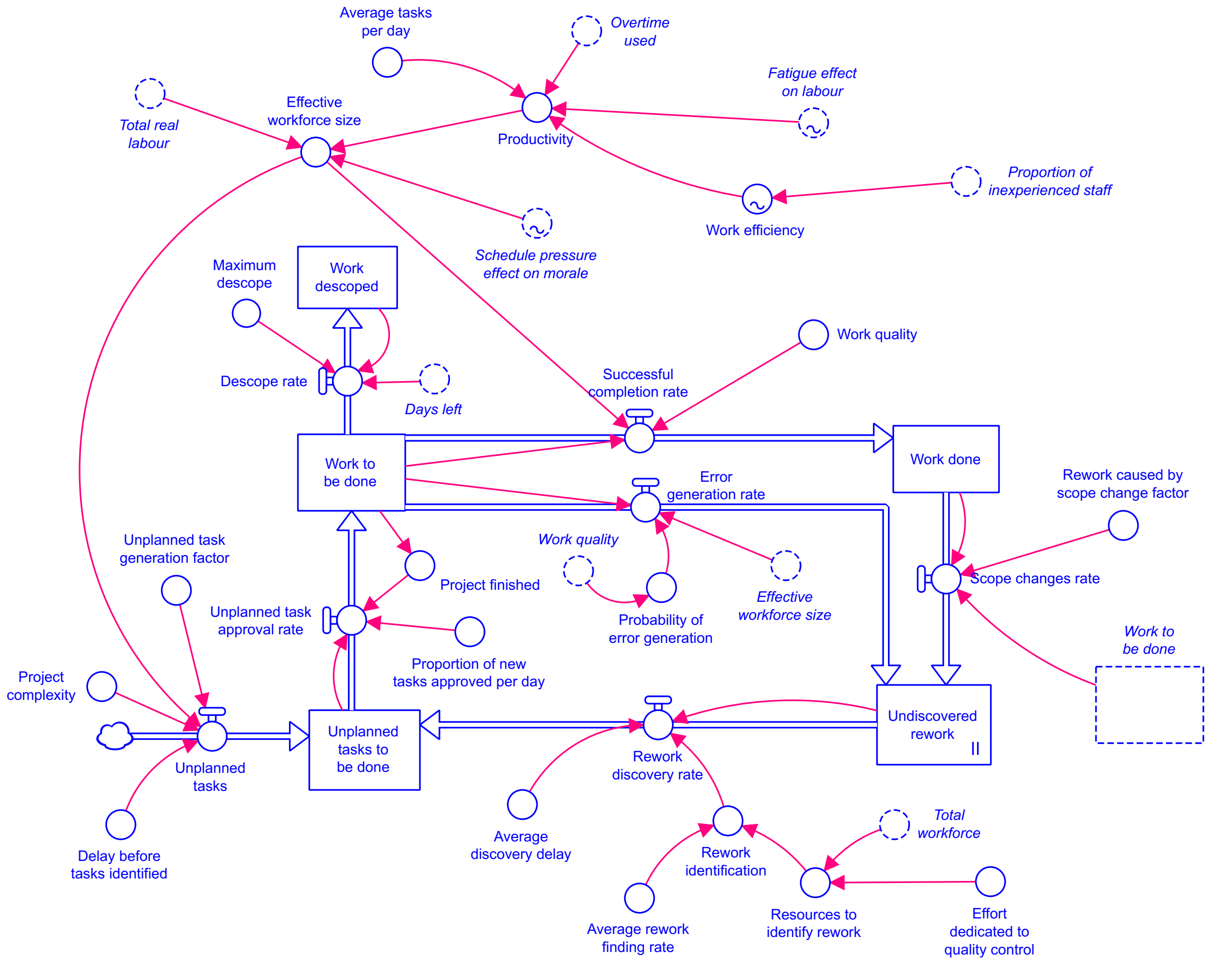

FIGURE 4 REWORK STOCK AND FLOW DIAGRAM INCLUDING PRODUCTIVITY

Figure 4 shows how the core of the basic model is extended to incorporate these factors and the productivity of staff. Note that variables shown with dotted lines represent ‘ghost variables’, defined elsewhere in the model, but repeated in another place to simplify the diagram. Without these ghosts, Figure 4, Figure 5 and Figure 7 would include many more interconnections.

3.2.1 RECRUITMENT MODELING

The mechanics of the recruitment cycle are shown in Figure 5, including the flow of resources through two stocks representing new and experienced workers, and also showing how the training cycle influences the total real labor available labor level and in turn the productivity of the team. As noted above, the model explores two scenarios – a fast hiring process in which new staff are in post within 30 days, and a slow process, in which it takes 120 days. The need for new staff is driven by the work to be done, the current productivity of the work team and the remaining time of the project. The initial stock of ten engineering staff reduces due to staff quitting with a baseline average time employed of 1000 days. This value is affected by staff morale, however, influenced by pressure to work overtime, especially when this is unpaid or paid at a low rate.

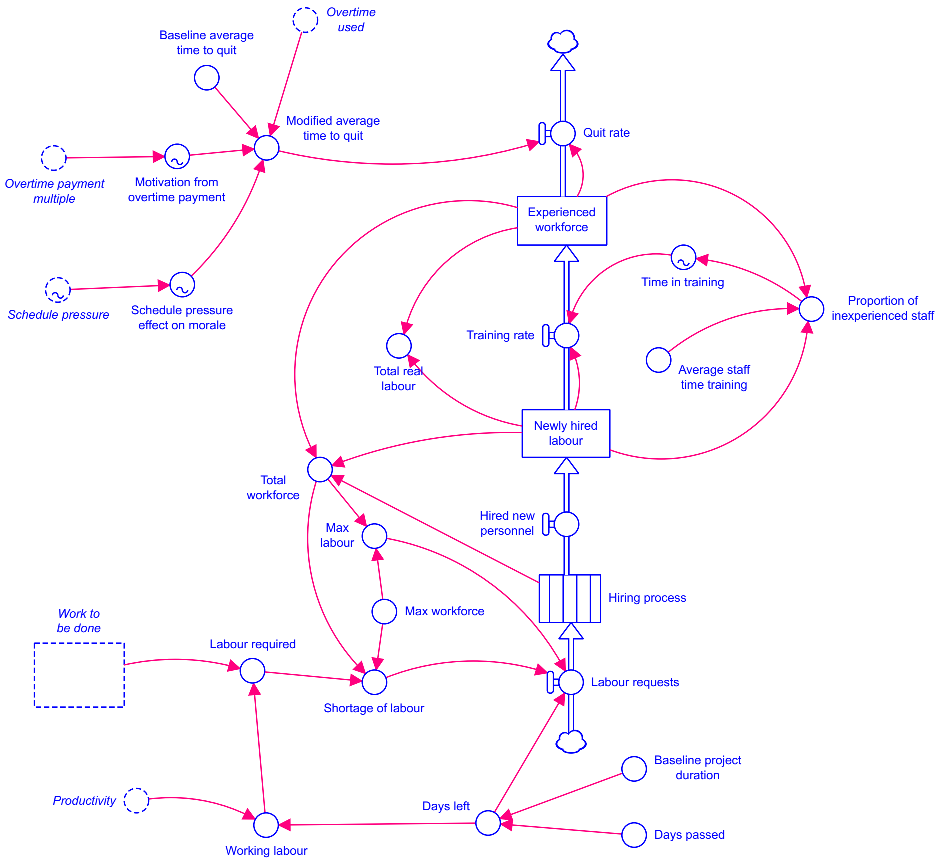

FIGURE 5 HIRING STOCK AND FLOW DIAGRAM

3.2.2 OVERTIME MODELING

The productivity of the team shown in Figure 4 is mostly defined by the hours of work per day; in this case, a baseline of 8 hours of work per day is assumed. Productivity increases directly as overtime hours are worked (in response to schedule performance deteriorating). Overtime leads to fatigue, however, which has a balancing effect on productivity, reducing the number of activities completed and increasing errors and rework (Lyneis and Ford 2007).

3.2.3 OVERALL RESULTS

During the simulations, a thorough evaluation of the performance of each variable over time was carried out to identify discrepancies, and to check the consistency of the results. Table 3 summarises the key results for various combinations of input parameters. These results all assume that any overtime undertaken (between 0 and 50% of the regular workweek) is unpaid. If payment for overtime is provided, staff motivation does not fall as rapidly as schedule pressure and working hours increase. Not paying for overtime in the short term leads to a relatively small increase in staff turnover and a small reduction in productivity but a significant increase in cost. For simplicity, these results are not shown in this paper.

It is worth noting that once rework and unplanned tasks feature in the model, performance deteriorates significantly. With the project team capped at the original level of ten engineering staff and with no overtime worked, the model shows a 35% cost increase and a 53% schedule delay, even when the replacement of staff that leave is implemented relatively quickly (30 day delay in the hiring process).

Figure 6 shows how the effective workforce size is diminished by the need to recruit and train new staff. Even when the team is working 25% overtime, the impact of staff turnover leads to a net productivity reduction of 17% relative to nominal productivity. Figure 7 shows the stock and flow model for the use of overtime. Schedule pressure builds as a project begins to run late, which ultimately triggers the use of overtime up to the maximum permitted level. This has a knock-on effect on fatigue and then productivity, and the payment offered for overtime influences the total project cost as well as the motivation as shown in Figure 5.

Max uplift of engineering staff	**Hiring delay (days)**	**Workweek uplift via overtime**	**Cost increase**	**Schedule increase**
0	30	0	34.5%	53.0%
0	30	25%	16.0%	30.4%

0	30	50%	8.0%	18.6%
0	120	0	36.0%	68.0%
0	120	25%	18.5%	55.0%
0	120	50%	6.0%	33.8%
50%	30	0	31.0%	14.1%
50%	30	25%	24.5%	7.5%
50%	30	50%	23.5%	6.5%
50%	120	0	32.5%	24.5%
50%	120	25%	17.5%	12.5%
50%	120	50%	17.5%	10.1%
100%	30	0	30.5%	5.9%
100%	30	25%	25.5%	3.4%
100%	30	50%	25.0%	2.9%
100%	120	0	32.0%	13.6%
100%	120	25%	18.5%	6.9%
100%	120	50%	19.0%	5.6%
400%	30	0	29.5%	1.6%
400%	30	25%	25.5%	1.3%
400%	30	50%	25.5%	1.2%
400%	120	0	32.0%	7.2%
400%	120	25%	18.5%	5.4%
400%	120	50%	19.5%	4.9%

TABLE 3: COST AND SCHEDULE IMPACT OF STAFFING STRATEGIES (WITH UNPAID OVERTIME)

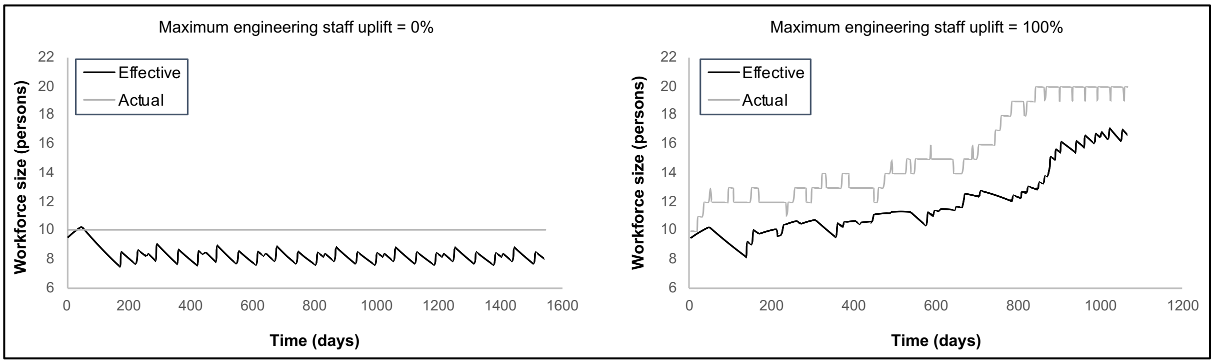

FIGURE 6 ACTUAL AND EFFECTIVE WORKFORCE SIZE (120 DAYS HIRING DELAY, 25% OVERTIME)

Even with significant unpaid overtime offered, if the project cannot increase its staffing level in the face of unanticipated tasks, then although cost performance may be quite good (only 10% over budget), it is inevitable that schedule delays of 20-30% will be experienced (Figure 8). It is worth noting that the delay in the process of hiring staff (either replacements for those leaving or new staff to grow the team) has a large impact on schedule performance, especially when overtime is capped at 25% (for headcount capped at the starting level, the project will be 30.4% late with hiring delay of 30 days, 55% late with a hiring delay of 120 days).

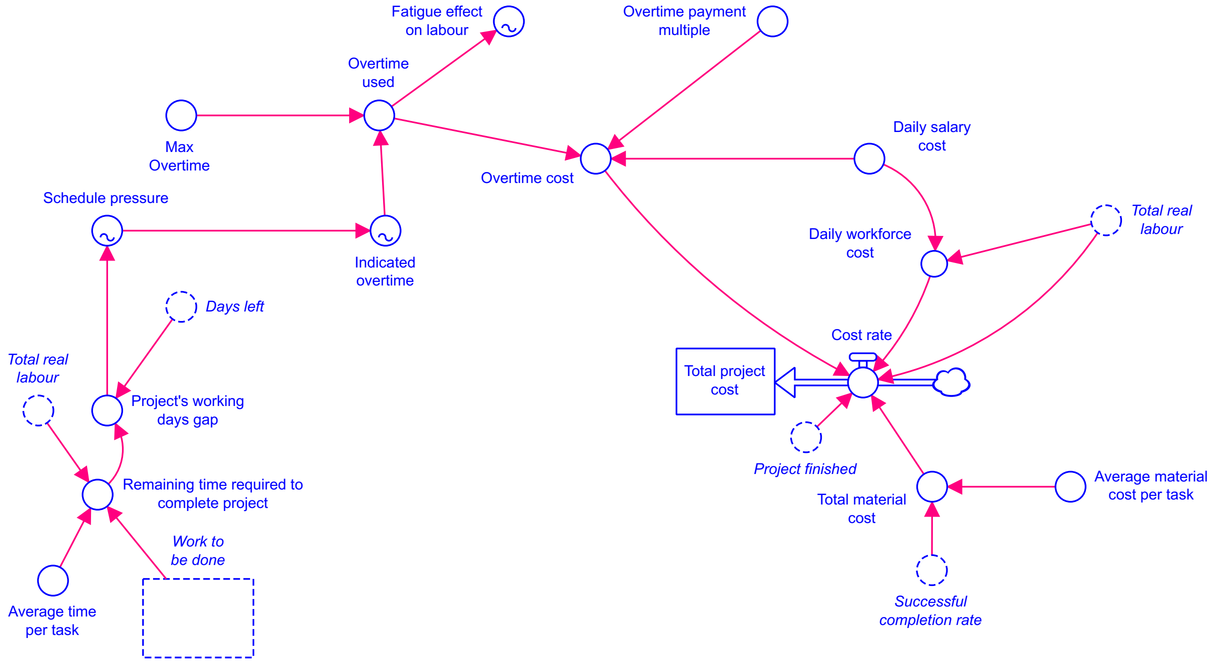

FIGURE 7 OVERTIME AND OVERALL COST ANALYSIS

When significant additional recruitment (doubling the engineering team) and unpaid overtime is possible, schedule performance may be quite good (typically less than 5% late), but cost increases of around 20% are experienced (Figure 9). Interestingly, assuming that the decision is taken to hire some additional engineering staff to improve schedule performance, the overall project cost is relatively insensitive to the decision of how much extra labour to hire after a point (50% uplift gives 17.5% cost increase, 100% uplift gives 18.5% increase given 120 day hiring delay and no overtime payment).

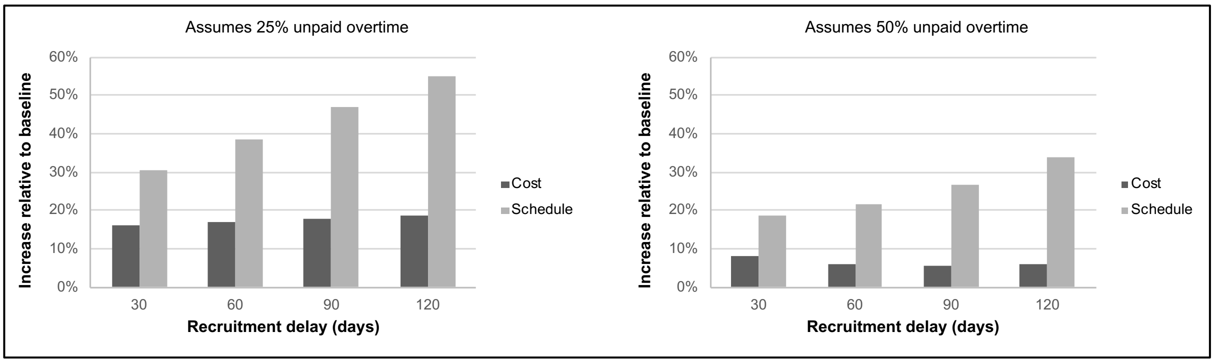

FIGURE 8 IMPACT OF HIRING DELAY ON COST AND SCHEDULE PERFORMANCE WITH HEADCOUNT CAPPED AT INITIAL LEVEL

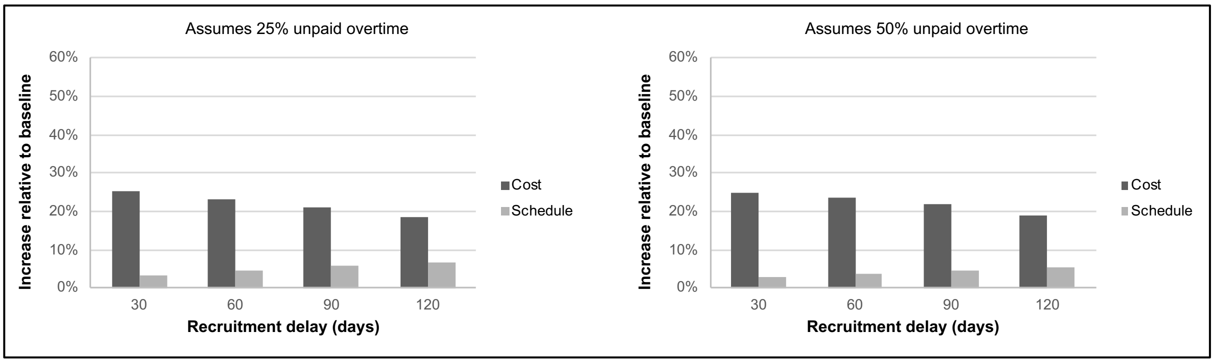

FIGURE 9 IMPACT OF RECRUITMENT DELAY ON COST AND SCHEDULE PERFORMANCE WITH HEADCOUNT ABLE TO RISE UP TO 100%

As the project progresses, rework and unplanned tasks must be completed in addition to the planned tasks. The relative contributions of these are shown in Figure 10. Note that this assumes a high level of work quality (90% of work is done correctly the first time), and a moderate level of project complexity (so the number of unplanned tasks is relatively small, reflecting a reasonably thorough job of risk identification at the proposal stage).

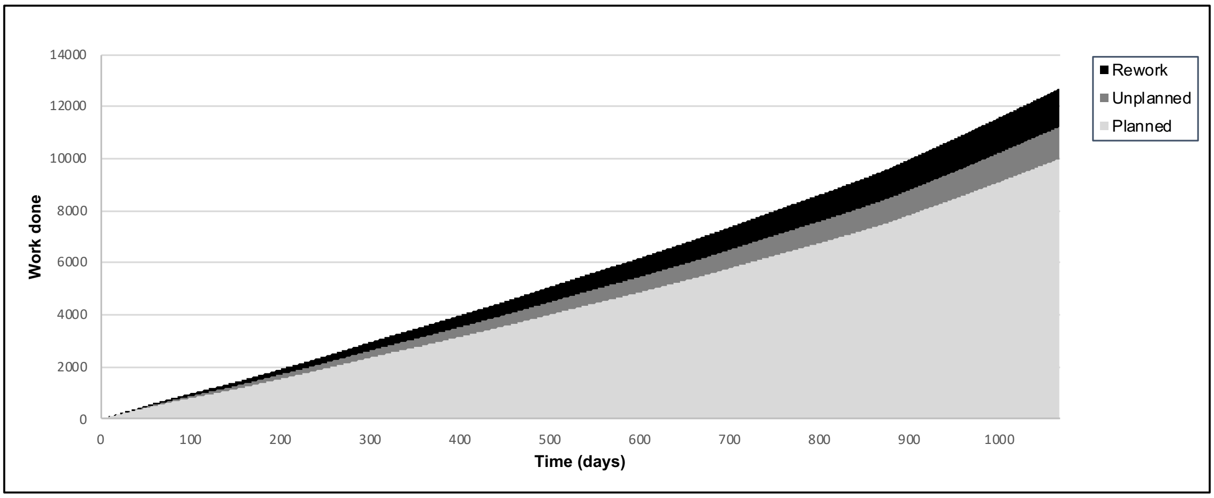

FIGURE 10 BREAKDOWN OF WORK DONE, WITH 25% OVERTIME, 120 DAYS HIRING DELAY, 100% MAXIMUM HEADCOUNT UPLIFT

4 DISCUSSION

4.1 IMPROVING PLANNING AND QUALITY TO REDUCE UNPLANNED TASKS

Cost and schedule overruns in projects are fuelled by the need to complete unplanned tasks. These stem from unanticipated complexity (as reflected in the model by the ‘project complexity' value) and rework, generated by low quality work. The culture or conspiracy of optimism mentioned in section 1.1.2 makes achieving realistic estimates challenging, however, so some level of unplanned tasks is unavoidable. Although it is relatively easy to imagine how the project would proceed if events unfolded according to the project plan, it is impossible to conceive the almost infinite range of low probability events that could happen during the project to cause significant delay. Anticipating and responding proactively to the risks that threaten the project's performance is therefore difficult, making most complex projects prone to cost and schedule overrun. It could even be argued that poor performance in projects is in general accepted or even expected, which could be considered a 'normalization of deviance'. This term was first used in the investigation of the Challenger shuttle disaster due to the insensitivity to unresolved technical anomalies that NASA apparently developed (Vaughan 1996), but it has also been used more recently in other sectors such as health care (Price and Williams 2018). In order to deliver projects successfully, several design and exploration loops are usually conducted to develop a thorough understanding of the system to be produced and the constraints of the project. Planning activities reduce the likelihood of failure, but their contribution to value is indirect (by reducing the probability of project failure) whilst they have a more direct cost, as they consume time and resources that could be spent on making more visible progress by starting the fabrication earlier (Wynn et al. 2011). Planning is, therefore, often not given as much emphasis as it should be, even though various studies have underlined its importance in the context of the business case for systems engineering (Elm and Goldenson 2012; Emes et al. 2012; Gruhl 1992; Honour 2004). Once the project is underway, the quality of work (via rework) has a significant influence on the generation of unplanned tasks; ensuring that appropriately skilled staff are hired, trained and motivated to produce their best work is important.

4.2 HIRING AND OVERTIME DECISIONS

The system dynamic modelling has shown how the cost and schedule performance of space projects can be controlled to some extent by the simple staffing interventions of hiring more engineers or varying the use of overtime. The models have demonstrated that these strategies can significantly impact performance, but achieving good cost and schedule performance simultaneously is likely to be elusive, consistent with the famous cost, time, quality triple constraint of project management (Atkinson 1999). Examining the hiring and overtime decisions at the disposal of project managers, it is clear that some combination of these is likely to be necessary to allow a complex project with significant unplanned tasks and rework to deliver within 20% of its original budget and schedule baselines. Performance at this level against both indicators, however, is likely to be impossible without considering a descope to reduce the level of technical performance delivered in one or more areas of the project. In complex projects, hiring additional staff is not a straightforward remedy to poor project performance, in particular, due to the productivity impact on existing engineers of having to train new staff (Brooks 1995; Reichelt and Lyneis 1999). Furthermore, it should be noted that without expanding the team, the quite extreme strategy of increasing the workweek by 50% without paying staff for the additional working time was unable to keep schedule delay much below 20%, even with a streamlined hiring process (increasing to nearly 34% with a slower hiring process, which is more typical of the space science institute).

It is assumed that the organization undertaking the project has no stock of unused experienced engineers that can be drafted onto the project at short notice. This would be the case in general, where a small, capacity-constrained organisation organization is conducting several important projects simultaneously. If instead, there were skilled engineers not currently working on other projects or working on low-importance projects, then some of these could be moved onto the more critical project temporarily, with schedule performance on any less important projects sacrificed. In the situation where new engineering staff needs to be employed, the hiring cycle may be constrained by the availability of labor with the specialist skills required. In the UK, there are skills shortages in advanced manufacturing (UKCES 2015) meaning short-term recruitment of extra staff is particularly difficult. Specialist skills for engineering in the space sector are particularly valued in the UK, where the sector has seen high growth compared to the rest of the UK economy over the last decade (UK Space Agency 2016). In the longer term, companies in developed countries often report difficulties in recruiting graduate engineers. In the US, a Deloitte and Manufacturing Institute report finds a widening gap between the jobs needing to be filled and the skilled talent capable of filling them (Deloitte and The Manufacturing Institute 2018). This has often been attributed to a shortage of science and engineering students (Royal Academy of Engineering 2017; Xue and Larson 2015), although other studies have challenged this conclusion – finding that in fact there are plenty of STEM graduates but too small a share of them go on to work in STEM jobs, preferring management (Charette 2013). Limited availability of the skilled staff sought increases the likelihood of a substantial delay to the recruitment process and may also provide a practical cap on the number of staff that can be recruited to the project.

4.3 LIMITATIONS OF THE MODEL

The model anticipates some of the real dynamics of a project team, including how schedule pressure and overtime pay may contribute to motivation. At this stage, the model still contains many simplifications, and as with all modeling, there is a degree of subjectivity in the creation of the model. For example, one area that has been considered but not yet implemented in the model is the possibility that, when schedule pressure increases, there is a drive to perform tasks concurrently and sometimes outside the regular and desired sequence (K. Cooper 1994; Ford and Sterman 2003; Lyneis, Cooper, and Els 2001). The engineering team would then have to make more assumptions to be able to progress with work concurrently, which would increase the chance of creating undiscovered rework. Although this concurrency would therefore have a first-order consequence of saving time, it has been suggested that concurrently executed tasks lead to a 5% error rate for complex projects due to these assumptions (H Nam Le, Wynn, and Clarkson 2012), fitting the archetype of a fix that fails to improve productivity (P. E D Love et al. 2002; Lyneis and Ford 2007; Wan, Kumaraswamy, and Liu 2013). The model also does not include any automatic corrective actions due to earned value or cost performance indicators; the system could seek to reduce the costs, for example, through saving in materials quality. So far, it has been assumed that for space projects undertaken, the quality requirements are inflexible.

5 CONCLUSION

This research provides an extension of the system dynamics rework cycle, such as developed by Reichelt and Lyneis (Reichelt and Lyneis 1999) based upon a case study of space projects that face the realistic need to conduct work that was not originally anticipated. The system dynamic model at the heart of the research is quite simple but has sufficient complexity to generate interesting results by exploring the causal relationships behind certain decision scenarios. In particular, it highlights the impact of using overtime and hiring strategies to address poor schedule performance. This model provides space project managers with an integrated way of understanding the non-linear dynamics that underpin the daily activities of the project team.

The model presented in this paper contains many assumptions. Values for key parameters have been obtained from the literature and in consultation with experts in the space science institute that was the focus of the study, but further work is needed to extend and calibrate the model with real project data, and to explore its implications in a broad range of situations. The model may be extended to explore: concurrency; variable material costs; gate reviews to check progress; availability and experience of different specialist roles, including, for example, various engineering specialisms, systems engineers, project manager and quality assurance specialists; different lifecycle models, including sequential models and iterative models (such as spiral or agile). Some of these changes may reveal opportunities to improve performance by reducing errors or inefficiency in projects.

The model finds that in a typical scenario with 25% unpaid overtime, even with 100% uplift in the engineering capacity of the team, there is a 6.9% increase in schedule and 18.5% increase in cost relative to the baseline. With no increase in staffing, the cost increase is the same (due to the inefficiencies with staff turnover, including replacement and training costs) but the schedule is extended by 55%. This shows that proactive hiring of additional engineering staff is an effective strategy even when financially constrained. This may be difficult to achieve in practice, however, due to the politics of making a case for increased employment in general, and also because in the space sector there may be limited availability of the specialist skills required. Achieving a good understanding of project complexity and the potential for the growth of unplanned work at the concept stage of projects is therefore crucial to ensure that cost and schedule baselines are realistic, otherwise overruns are ultimately unavoidable.

ACKNOWLEDGEMENTS

The lead author is recipient of a Ph.D. scholarship from the Republic of Ecuador Government as part of the program SENESCYT/IFTH “Convocatoria Abierta 2016”.

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