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AIRCREW MANPOWER SUPPLY MODELING UNDER CHANGE: AN AGENT-BASED DISCRETE EVENT SIMULATION APPROACH

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ABSTRACT

This paper deals with manpower planning using a dynamic and interactive simulation system that is agile and adaptive to robustly accommodate change - without requiring a complete rewrite. The simulation architecture extends the current hybrid modelling paradigm which integrates agent based (AB) constraints and controls with a discrete event simulation (DES) methodology. This allows for a more expressive, authentic representation of both process flows and agent policies that captures the advantage of system dynamics (SD) modelling by integrating agile controls with response feedback. This approach is inspired by the need to develop an aircrew training pipeline simulation for the Australian Defence Force (ADF) that supports the real needs for strategic manpower planning in a context of policy and requirements change management. A case study is provided to illustrate the challenges and approach.

1 INTRODUCTION

The ADF is continually looking for greater efficiencies in its training and operations. These include infrastructure consolidation, new initiatives, reconfigurations as well as policy changes – all having new demands on manpower requirements and flows. For example, basic helicopter flight training components across multiple services are currently being consolidated into a single location. Other types of changes include phasing out platforms, introducing new technologies, consolidating schools, restructuring training facilities and other training resources. Changes like these are common, illustrating that the system is in a constant state of transience and that inevitably causes perturbations in the flow of students through the training program.

However, these infrastructure changes are not the only changes in defense. The policies that govern training in individual schools and squadrons are also susceptible to change. For example, changes in school pass rates can severely impact on the predictability of graduate supply to operational squadrons. Equally, sudden changes in workforce attrition have implications on capability sustainment and recruitment needs.

Whether the changes are driven by internal initiatives or are imposed by the changes in the environment, the decision makers need to respond to these changes and insure both smooth transitions as well as longer term sustainment strategies. Clearly, there is a need for an organization such as the ADF which operates in dynamic and complex environments to create and maintain internal knowledge for better decision making (Baškarada et al. 2016).

This work is motivated by the need for a decision support environment capable of overcoming the challenges posed by dynamic nature of infrastructure and policies in defense. In particular, this paper discusses a user-driven solution to manpower planning, designed to be agile in addressing the needs of the

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ADF. These include current and projected view of the training system at hand, as well as the ability to perform strategic *what-if* analyses, to improve the efficiency and operational effectiveness. To model such changes, while preserving a common simulation architecture, there needs to be an easily reconfigurable simulation architecture capable of explicitly representing the changing infrastructure, domain policies, constraints and flows. This approach has the benefit of decreased effort in re-building models while providing a repository of historical changes that all translate into significant cost benefits.

The paper is organized as follows. Section 2 presents related work, while Section 3 describes the simulator design, covering design considerations leading to the proposed architecture. Implementation, verification and validation of the simulator is discussed in Section 4, followed by the detailing of a case study in Section 5. Section 6 concludes the paper.

2 RELATED WORK

Optimization and Simulation play important roles in manpower planning. As for the former a number of formulations have been explored including integer linear programming (ILP) for recruitment/workforce supply optimization. For example, Taiwo (2007) used ILP for the determination of effective workforce size while Azimi et al. (2013) used linear programming to allocate staff within a very practical setting: an Iranian beverage company. From as early as 1971 (Bartholomew 1971) Markov processes have been used to model recruitment and manpower training as a stochastic dynamical system where basic recruitment and progression-through-training were defined as prior probabilities of being accepted into a program and progression defined in terms of Markov transition matrices. Markov Decision Processes (MDPs) have also proved useful in providing explicit variables for recruitment actions and rewards to derive optimal recruitment policies (Berthelsen 2008, Udom 2013).

Markov and MDP formulations for manpower planning also share one core feature with the second, simulation approach. They are both essential discrete time dynamic systems. The difference lies in simulation providing very important *what-if* scenario examination while the Markov and MDP approaches offer "once-only" solutions. They also are limited in so far as they do not allow for the exploration of the differential contributions of specific features, policies, etc. The appropriate AB-DES framework is ideally designed to this end. It is not so much about optimization as it is about the user gaining insights to then enable a more relevant optimization formulation.

Simulation as a technology for manpower planning and supply modelling in defense has already been shown to be useful (Davenport et al. 2007) to some extent. That is, previous simulation models do not easily accommodate dynamic changes in infrastructure, resources, policies and flows over-time. To address this requirement, an agent-based simulation architecture (Borshchev and Filippov 2004) is explored in this study where schools, instructors and students are defined as independent entities making decisions about their actions and interactions based on a set of rules governing their behavior. Additionally, agent based models permit individual student tracking (Bonabeau 2002). Heath et al. (2011) presented an interesting discussion on cross-paradigm simulation modelling by comparing pairs of different simulation paradigms (e.g., SD-DES, AB-DES, SD-AB). They argue that the AB-DES approach is suited to modelling any situation which includes resources that must perform activities as well as human interactions where individual behaviors determine how these activities progress. This is our case with manpower supply management under change.

SD and AB have been used together to simulate healthcare systems where the SD model provided high abstraction levels (of a large scale system) while individual workflows of person were modelled as agents (Djanatliev and German 2013a). However, modelling lower level details requires ordered sequences of individual events necessitating the inclusion of a DES where agents are dynamically generated from the SD and then DES is used for process modeling - for example, in individual hospital operations as investigated by Djanatliev and German (2013b).

DES and AB have been used together to simulate the dynamic allocation of human resources to affect a production process (Montevechi et al. 2015). Here, the inclusion of AB was justified to expand the "computational ability to mimic" natural human behavior (p.1570). It was also argued that the interaction of independent agents "by definition cannot be reduced to parts of the system because of the interaction among them" (p.1562).

Anagnostou, Nouman, and Taylor (2013) and Fakhimi et al. (2014) developed a distributed AB-DES based simulation framework to support strategic and operational decision making in emergency medical services. The framework consisted of individual federated models, ambulance (AB based) and accident & emergency (DES based). The communication between which was handled by operations and data exchange middleware.

Another demonstration of a multi-paradigm reconfigurable AB-DES is the recent work of Liraviasl et al. (2015) for manufacturing. Their system aimed to rapidly adapt factory configurations to meet the needs of changing customer demands, new technologies, and continuing needs for efficient manufacturing under change. Their multi-paradigm model allows for on-line layout changes by reconfigurable logic controls consisting of both agent state and agent-agent coupling updates. These control different parts of the manufacturing system so that they can be updated as a function of requirements. For example, the reallocation of an idle machine to different objects, tasks or order changes requiring relocation of resources. This adds an additional on-line reconfigurable processes to the type of system developed by Anagnostou, Nouman and Taylor (2013).

In all, there is strong evidence for the use of an AB-DES for manpower management under change and the remainder of this paper deals with this issue in the context of aircrew training.

3 SIMULATOR DESIGN

A training pipeline simulator was specifically designed and developed to provide long term support to manpower planning needs of the ADF. The high level requirement for the simulator is to represent the training continuum network at the adequate level of fidelity and to effectively facilitate evaluation of policy options.

The training continuum spans a network of training schools, starting from recruitment until graduation, i.e. entering the operational squadrons. Each student path follows a tailored training program. Factors that affect student progression through the continuum include instructor and resource availability (including aircraft and various types of aircraft simulators), student pass rates, school policies, graduate targets at individual schools, as well as other changes to operational squadron requirements. The way we accommodated these requirements is described in the section below.

3.1 Design considerations

Capturing the transient nature of the system is important but rarely achieved since it typically involves enumerating all possible system states and then developing procedures for determining what particular states and state changes are best applied to given situations and processes. This is difficult to achieve *a priori*. In the case of defense training a number of evolutionary changes as well as some common perturbations are very predictable. These include:

- Adding, moving or removing a squadron from the network
- Adding, moving or removing a school from the network
- Adding, modifying, moving or removing a course from any school in the network
- Adding, moving or removing resources from schools and squadrons (i.e. aircraft, simulators, instructors etc.)
- Policy changes such as priority servicing, attrition, pass/fail rates and their variance etc.

Figure 1 illustrates the types of time based structural and parametric changes to the training network. The following characteristics of such time dependent (evolving) changes to training scheduling and planning are key to the AB-DES system design.

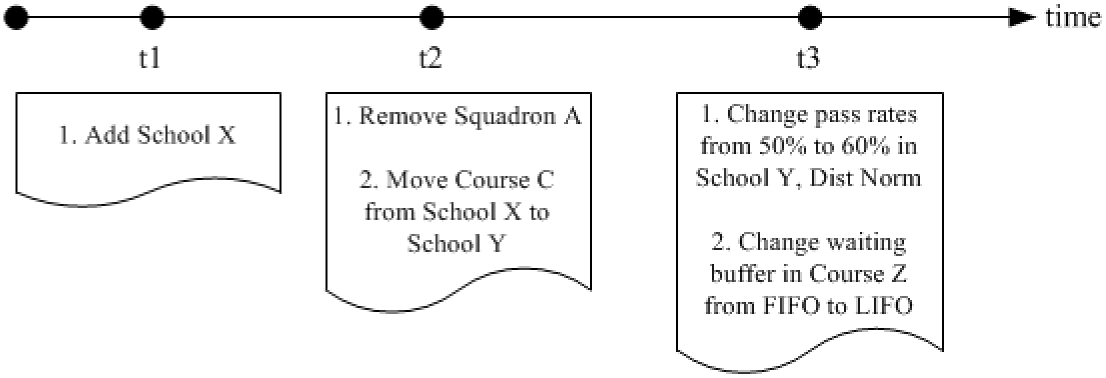

Figure 1: Possible changes to the training continuum over time.

The transient nature of network structure and flows. The network needs to be dynamically reconfigurable whereby schools or squadrons can be added or removed from the network, courses can be created or modified, resources (both human and infrastructure) can be added or removed from the system throughout simulation at runtime. To address such needs we have adopted an object-oriented design where all the simulated components in the system are modelled as individual classes of objects. This enables decoupling of the system components to provide greater control and flexibility and independent adjustment of parameters associated with the respective objects.

Individual tracking and decision logic. It is critical that the simulated human entities in the system are distinguishable - students have their training paths and records, and graduates have their own career paths, posting history and preferences. That is, each node in the training network is an entity on its own with its unique set of decision logic that represents the policies of a given school or squadron. This can create conflicts such as a policy priority allocations of Navy over Army students for over-subscribed courses. Such conflicts can be resolved via agent heuristics within the AB-DES approach.

Internal feedback loops. Unlike typical production or manufacturing processes where a product, once created, exits the system, graduates in our case do not always exit. Some of them eventually become instructors and therefore continue to play a role in the training continuum. This makes the training continuum a closed-loop system with transient, hitherto unpredictable needs for significant, urgent new student intake. A school's capacity to train students depends on the available number of instructors. The number of instructors supplied to schools depends on the number of graduates in the previous years. This illustrates the feedback loop that is difficult to manage due to the latency in the network and the unpredictability of graduates numbers. This type of behavior is typically modelled using the system dynamics approach and is incorporated into our simulator design.

What-if analysis of strategic policies. The fundamental requirement of this work is to simulate the execution of different policies and analyze the impact of such decision. For example, in order to achieve specific workforce target level, a school might temporarily contract additional civilian instructors to increase its training capacity and, thus, increase its throughput of students. Alternatively, if temporarily decreasing workforce attrition rates has a positive impact on achieving and maintaining desired workforce level, a decision maker can then employ various incentives to influence staff retention. The tweaking of these key input parameters, or *levers*, and seeing how sensitive the system is to the change in that parameter are important for decision analysis. The proposed AB-DES approach allows the simulator to accommodate such heuristic events without fully reconfiguring the system.

3.2 AB-DES Architecture

The conceptual model of the manpower training continuum utilizes both discrete event and agent-based simulation approaches, whilst encapsulating the lever control and feedback loop elements that were previously modelled using the system dynamics approach (Johnstone et al. 2015). The simulator's architecture is illustrated in Figure 2.

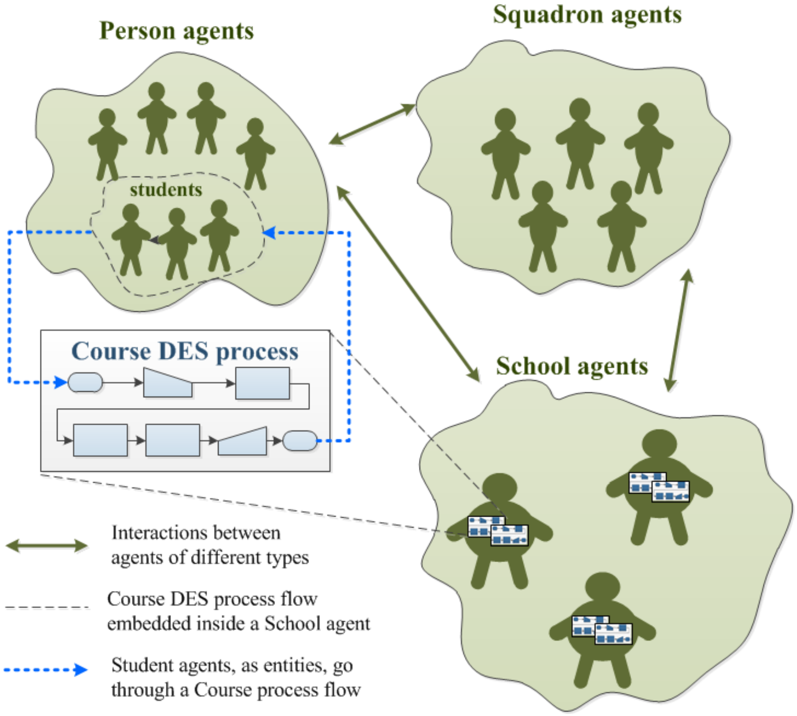

Figure 2: The AB-DES training simulation architecture.

Students, instructors and other trained personnel have their own specific behaviors and are modelled as autonomous agents (*Person agents*). Schools and squadrons have local policies (rules) that govern their decision making and are also modelled as agents (*School* and *Squadron agents*). On the other hand, processes involved in running a course require discrete event simulation in order to faithfully model the sequence of activities and depict bottlenecks and queuing at the resource level. As such, courses are modelled as *Course DES process flows*. Courses are run under the umbrella of their respective school policies, whilst utilizing schools' resources. Therefore, the Course DES process flows are embedded inside School agents. Students (a subset of Person agent population) that undertake a training course go through a specific Course DES process flow, during which they are simply treated as homogeneous entities. Various interactions take place between agents of different types. Squadron agents set the constraints for school intakes, a downstream school also influences the upstream school's intake, students get posted to squadrons or schools upon graduation and more.

This architecture reflects the natural structure of the aircrew training continuum. This object-oriented, multi-method simulation architecture enables the system to be runtime reconfigurable. A new school, squadron or course object can be dynamically created, a course's capacity or duration can be altered throughout the simulation, and student training paths or personnel career paths can be redefined at runtime.

This design also enables the easy implementation of the instructor feedback loop. A Student, once graduated, joins a squadron's workforce as a *Trained Personnel*. The Squadron agent periodically decides how many of its workforce to send back into the training continuum to train and become instructors. The selected Trained Personnel becomes a Student and upon completion of instructor training transitions to be an *Instructor*. These states of one's career are modelled as a specialized type of a Person agent (Figure 3).

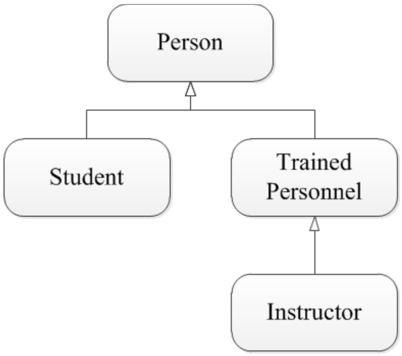

Figure 3: Specializations of the Person agent to represent simulated career states.

3.3 Scenario configuration

To support decision makers in formulating hypothetical scenarios the simulator design incorporates the concept of *Action*, *Targets* and *Probes*. An Action is a user-specified, time-based event that changes the value of a selected input, or lever. A Target is used to specify a desired value of a simulation parameter. A Probe is used to indicate whether a specified Target can be achieved by a specified point in the simulation time, given the scenario settings. Figure 4 illustrates a series of Actions, Probes and Targets, created for a scenario and displayed along the simulator's timeline graph. The lighter shaded area depicts the projected statistical summary for a particular parameter from current time into the simulated future.

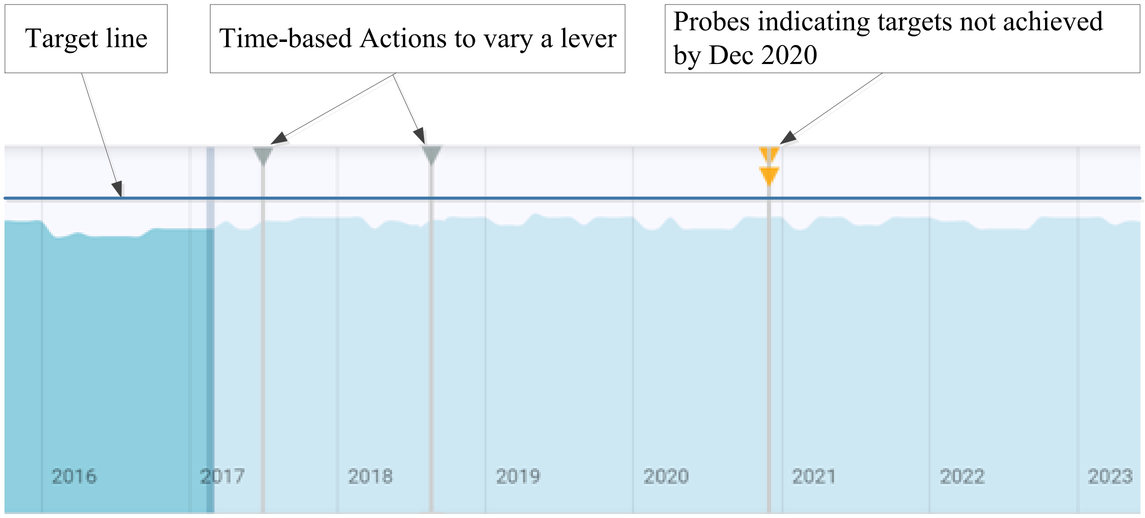

Figure 4: Simulator's timeline chart showing a scenario's time-based *Actions, Target* and *Probes*.

4 IMPLEMENTATION, VERIFICATION AND VALIDATION

4.1 Simulator Development

A prototype model was initially developed in AnyLogic (Nguyen et al. 2016) to validate the conceptual design for the simulator. It was then transitioned into web-based software using an in-house Java–based AB-DES simulation engine. The software also has an interactive user interface that allows intuitive generation and manipulation of *what-if* scenarios. Visualization of data pipelines has been designed to provide an aggregate view of the underlying student flows, all with visual cues for speed of traffic and color diagnostics indicating excessive bottlenecks and underflows. The statistical summary is displayed in the simulated timeline, as seen in Figure 4.

4.2 Verification and Validation

To ensure the design, functionality and processes built into the simulator accurately represents the behaviors of the real-life training network, verification and validation were continually conducted in a piecewise fashion throughout the development of the simulator. The student paths and flows were individually verified for each student type through tracing. Then the compounded total picture with all student paths was verified through extreme condition and degenerate tests. Given the model has a number of stochastic components such as student pass rates, Monte Carlo simulation was used to obtain the average annual flows and compared to the anticipated spreadsheet static solution. Finally the model has been face-validated against existing client historical data and by subject matter experts.

5 CASE STUDY

This section details an anonymized case study that was conducted in response to a current ADF requirement. The objective of the study was to identify levers (and levels they should be set at) in order to increase the aircrew population to a desired target of 80 within three years, starting from 2017. *Levers* are the predefined simulation parameters (such as a school's capacity or an attrition rate) that a decision maker can vary in order to explore the impact on the study's objective.

The analysis was conducted using the branch-and-bound technique. The initial scenario was *status quo* (i.e. baseline), where the system was configured to a current state of the aircrew training network as detailed in Tables 1 to 4. This included the current resource profiles at training schools and the current aircrew attrition rate of 7%.

Table 1: Current and target aircrew workforce size.

Current aircrew population	70
2019 target size	80

Table 2: Annual aircrew recruitment data.

Intake Type	Annual recruitment
inA	3
inB	3
inC	1
inD	3
Total	10

Table 3: School data.

School	Maximum Capacity	Pass Rate
scA	N/A	90%
scB	N/A	90%

scC	5 per course	60%
scD	5 per course	90%
scE	3 per course	100%
scF	2 per course	100%

Table 4: Initial aircrew training continuum state.

School	Students in training	Students in queue
scA + *scB*	5	N/A
scC	6	5
scD	6	5
scE	3	4
scF	2	0

Each consecutive scenario included changing one lever setting at a specified time point, thus enabling a structured way of exploring compound changes through the depth-then-breath tree. Branches that could no longer be exploited were eliminated from the future analysis.

The output relating to the baseline scenario is shown in Figure 5. Here, the horizontal line represents the desired target level. For this scenario, the simulated aircrew workforce level by end of 2019 is 71, which below desired target of 80. Additionally, the trend appears stationary, indicating that the training continuum is able to sustain current aircrew levels but requires intervention to increase and sustain the workforce to the desired target. At another part of the training network, leading up to the end of 2019, the queue of students waiting to commence at *schE* was continually growing, as shown in Figure 6, indicating a bottleneck at this node. This discovery guided the next lever to be pulled which could resolve this blockage in student flow. Therefore, the next scenarios to be considered were increasing capacity in this school and reducing attrition in the squadron being supplied by *schE.* A summary of scenario analysis is provided in Figure 7.

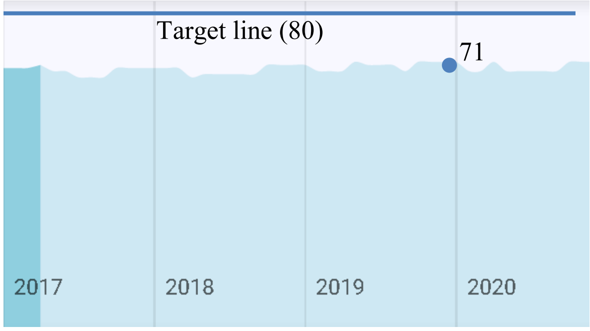

Figure 5: Aircrew workforce level in the baseline scenario.

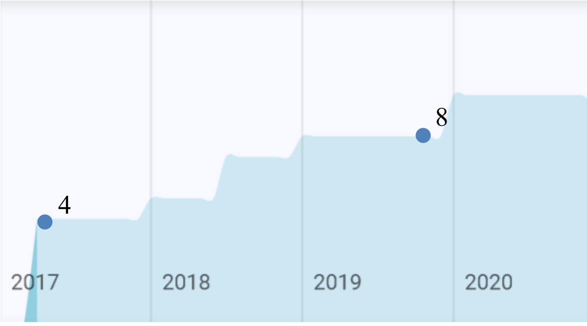

Figure 6: Input queue at school *scE* in the baseline scenario.

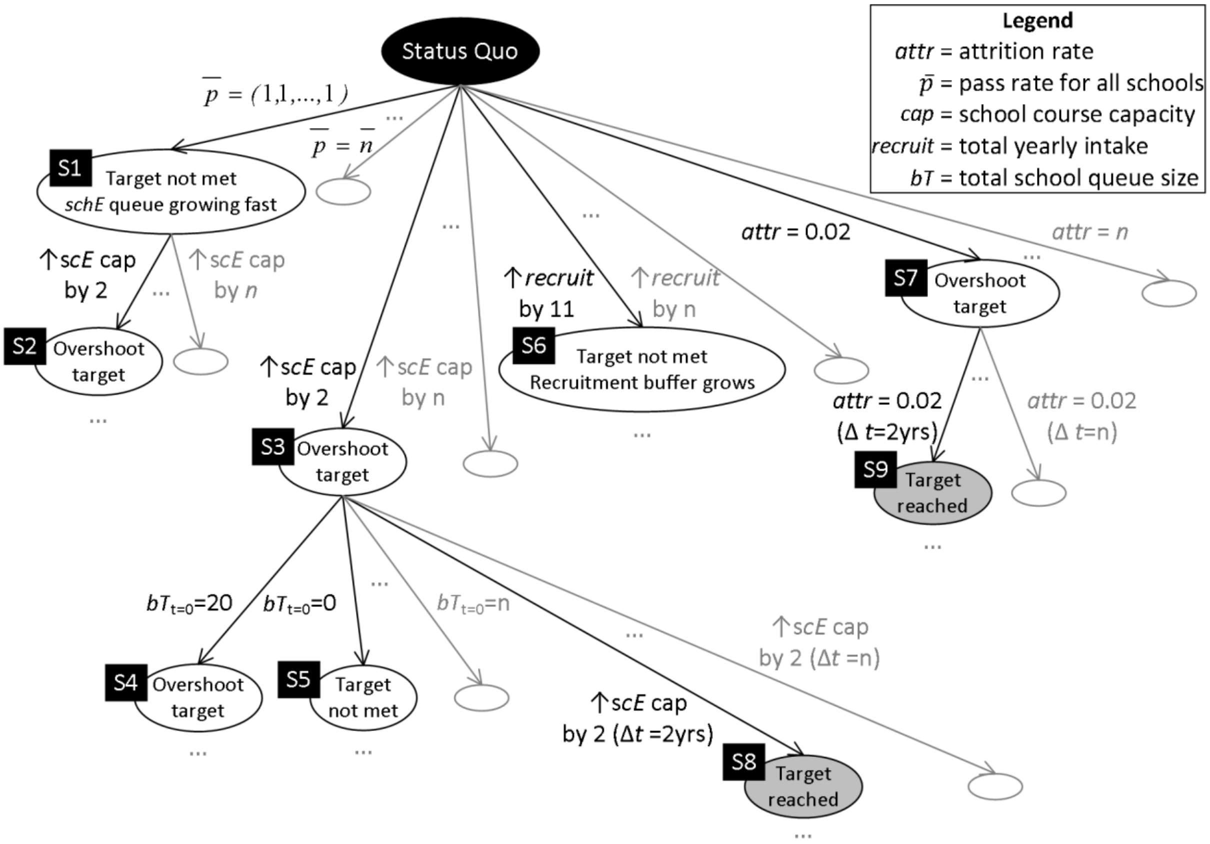

Figure 7: Branch-and-bound scenario exploration tree.

Unlike classical optimization where only one solution (the "best") is of interest, here there are multiple "*good"* answers which need to be evaluated and their "*goodness"* is not necessarily a final evaluation. A good solution today may not be the best in two years' time, given the consistently changing environment. Therefore, the objective here is to provide a structured environment for decision makers to explore all possible choices in levers, at a given time, and their implications. The choice as to which lever to pull is left to the user given the risk implications they are prepared to accept. The software allows them to see the implications of their decision on the entire system from present time played into the future.

6 CONCLUSION

This paper explores the use of a hybrid, agile, interactive AB-DES architecture with branch–and-bound scenario exploration, for manpower planning the context of aircrew training pipelines in the ADF.

The transient, constantly evolving nature of the training continuum was the major design consideration for the proposed framework. This object-oriented hybrid design enables the model to be dynamically reconfigurable to allow for the changing number of schools and courses throughout the simulation, as well as the ability to adjust the affected transitions between courses accordingly – as illustrated in the case study.

The use of agents to model students and instructors and their individual behaviors has proven to be an efficient way of introducing a level of autonomy in the model. Moreover, the modelled agents can be expanded to include more complex behaviors and decision making heuristics if needs arise. This is particularly important in modelling various governing policies at the school and squadron levels. The use of discrete event process flowcharts to model sequences of activities involved in running a course as well as the use of DES resource management functionalities proved to be beneficial. This approach allows for the identification of potential bottlenecks and to analyze resource utilization. The process flow charts can be expanded to include more complex activity flows without affecting the overall model.

By combining AB and DES approaches, the hybrid model can accurately represent both the process-centric view of the system as well as model individual-centric aspects of the training continuum. The proposed architecture is applicable for both static and dynamic training pipelines that involve autonomous, though interdependent, entities going through a series of training activities which could require both human and material resources. The simulator combined with scenario and what-if analysis capability proved to be beneficial as demonstrated by the case study. Our military decision makers were able to explore and evaluate various policy options and examine the impact on the training network instantaneously.

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