22nd National Conference of the Australian Society for Operations Research, Adelaide, Australia, 1–6 December 2013
www.asor.org.au/conferences/asor2013

Operational Synthesis for Small Combat Teams: Exploring the Scenario Parameter Space Using Agent-based Models

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Abstract: Combat simulations and wargames form part of a suite of tools used in the analysis of military operations. Operational synthesis is a technique that integrates a class of models known as agent-based distillations (ABD) into the analytical process. ABDs are a subset of agent-based simulations that deliberately distil the modelling variables in order to focus on those that are important for the purposes of the study. This property makes ABDs particularly useful for the rapid exploration of large parameter spaces, something that is not typically feasible in high-fidelity military simulations due to resource and computational constraints.

In this study we explore the utility of the operational synthesis approach in the context of the performance of small combat teams conducting close combat in an urban setting. We examine the ability of the Map Aware Non-Uniform Automata (MANA) ABD to independently identify trends that are consistent with those found in a previous study that was conducted using a mix of wargaming and high-fidelity closed-loop simulation with the Close Action Environment (CAEn) tool. The CAEn study developed a scenario to assess the impact of various manned and unmanned vehicle options on the combat performance of a small combat team for the break-in and clearance of a small village. We modelled the same scenario in MANA to explore the impact of terrain density and opposition tactics and force size on the outcomes.

The results from the implementation in MANA show trends consistent with the CAEn study. Some noticeable differences were observed in the case of civilian casualties but these results can be attributed to known limitations of both the CAEn study and some parameters in MANA. We also identify additional insights that warrant further study with other tools and techniques. Further work is also required to determine if similar outcomes can be achieved for a range of different military scenarios. If the results from studies conducted using ABDs consistently align with other studies then ABDs would be a valuable addition to the suite of military operations analysis tools given their ability to explore vast parameter spaces in a relatively short period of time. ABDs such as MANA could then be exploited to provide initial insights during the problem definition and design stages of relevant military studies and also to add robustness during the analysis phase.

Keywords: *Agent-based modelling, Defence, Simulation, Operations analysis*

1. INTRODUCTION

Operational synthesis is an analysis technique developed by the US Marine Corps Combat Development Command to integrate a range of military simulation and decision support techniques to help overcome the limitations of each individual tool (Horne, 2001). The application of multiple techniques to explore military problems is not a new concept (see Bowley et. al., 2003). Operational synthesis is unique in that it integrates a class of models known as agent-based distillations (ABDs) with other modelling techniques such as wargames, seminars, high-fidelity simulations and deterministic models.

ABDs are a subset of agent-based simulations, and as the name implies, deliberately distil the attributes of a model in order to capture the key aspects of the situation (Horne, 2001). In the military context ABDs typically use simplified models for representing terrain, detection and weapon properties. The simplicity of ABDs makes them useful for the rapid exploration of large parameter spaces, a process referred to as data farming (Horne, 2001). Data farming is not normally feasible with high-fidelity military simulations due to high resource and computational overheads. ABDs can potentially help address this limitation if they can be shown to produce results consistent with higher fidelity simulations. Tailby et al. (2001) conducted an operational synthesis study and found a "weak link" between the ISAAC ABD and the CASTFOREM simulation for a reconnaissance and surveillance scenario. Anderson et al. (2003) found that the MANA ABD showed a "reasonable match" for results from *Janus* wargames while investigating the utility of a surveillance platoon.

This paper investigates the utility of an updated version of the MANA[1] ABD (McIntosh, 2009) as an operational synthesis tool. Consideration is given to MANA's ability to both add robustness to results already generated by high-fidelity simulations and as a tool to generate initial insights to guide the direction of more detailed studies. We use MANA to replicate a previous study[2] conducted using the high-fidelity Close Action Environment (CAEn) simulation to determine if consistent results can be obtained. The CAEn study examined the performance of micro combat teams (MCT) conducting close combat in an urban setting and investigated three different levels of vehicle protection and two unmanned vehicle options. This study was chosen for the MANA replication because it has a mix of human and vehicle entities and is indicative of the nature and scale of typical CAEn scenarios. We then apply data farming to the MANA scenario by running simulations for multiple combinations of the variables associated with terrain and the location and size of opposing forces in order to investigate the robustness of the CAEn results. Given the limited fidelity of ABDs, the intent is not to produce identical output but to achieve trends consistent with CAEn in order to add confidence to the insights generated by the data farming.

2. OVERVIEW OF CAEN STUDY

The previous CAEn study addressed the impact of vehicle options on the combat performance of a MCT for the break-in and clearance of opposition forces (OPFOR) from a small village. Three different manned vehicle protection options were made available to the experimental force (EXFOR): light, medium and heavy. In addition, three different levels of unmanned ground vehicle (UGV) enhancement for EXFOR were explored: no UGVs (Option A), three small, lightly protected UGVs (Option B) and one larger, heavily protected UGV in addition to three small ones (Option C). A baseline scenario was also modelled in order to consider the relative improvement of the other options. Of the ten combinations, only six were examined in the original study (shaded in Table 1).

Table 1. EXFOR manned and unmanned vehicle options.

	A: No UGVs	B: 3 Small UGVs	C: 3 Small and 1 Heavy UGV
1: Light Protection	A1	B1	C1
2: Medium Protection	A2	B2	C2
3: Heavy Protection	A3	B3	C3
Baseline	Baseline		

The EXFOR order of battle (ORBAT) consisted of the MCT and an attached tank section (2 tanks), a five person Manoeuvre Support section mounted in an Infantry Fighting Vehicle (IFV) and a five person Joint Offensive Fires Team (JOST) also mounted in an IFV. The MCT consisted of three sections, each of which was divided into two fire teams of four. In support, but not directly under the control of the MCT commander, were indirect fire weapons and unmanned aerial vehicles (UAV). The OPFOR ORBAT comprised of infantry containing a 13 person conventional state element and a 22 person insurgent element.

[1] The version used in this study is MANA 5.00.98

[2] The study referred to is documented in an internal Defence report.

OPFOR weapons consisted of rifles, machine guns, grenade launchers, an anti-air weapon, rocket propelled grenades (RPGs), suicide bombers and a single improvised explosive device (IED).

The CAEn study also included three types of civilian elements. There were: 30 static civilians who would remain indoors and away from the combat; 20 mobile civilians were modelled to represent people moving around the village running urgent errands; finally, eight civilians who were sympathetic to the OPFOR provided them with additional situational awareness (SA) by communicating EXFOR locations.

The data collected during the CAEn wargames was run 200 times in the closed-loop format of CAEn for statistical testing. The metrics were mission success, EXFOR casualties, civilian casualties, IFV casualties and OPFOR casualties. Mission success was defined as clearing the allocated clearance without losing a critical asset such as an Armed Reconnaissance Helicopter (ARH) or a tank.

3. METHOD

3.1. Implementation in MANA

To convert the CAEn scenarios into MANA a number of changes were made. The reasons for these changes can be separated into three main categories. The first category arose as a result of the combination of the unintended effects of wargaming multiple scenarios and the limitation for current military simulations to dynamically reproduce plausible military tactics within a feasible timeframe. The second types of changes were those forced by the lower fidelity of MANA while the final changes were deliberate distillations made by the authors. We will initially discuss the first of these three categories.

In the MANA conversion it was decided that in all scenarios EXFOR would use a fixed tactical plan to accomplish their objective which is also referred to as a Scheme of Manoeuvre (SoM). During the CAEn wargames it was noted that EXFOR used a different SoM in each scenario, sometimes the changes were subtle while others were significant. These changes were made in order reduce the impact of any learning effects that OPFOR might have achieved based on the outcomes of previous scenarios. In addition, it was also difficult to determine exactly when and why certain EXFOR elements were being employed and/or dismounted. As a result it was decided to remove the ARH from the EXFOR ORBAT and to model the Manoeuvre Support section and JOST as single IFVs with no attached personnel. In addition, it was decided that there would be no embussing and debussing and that EXFOR infantry would always operate dismounted. The revised ORBATs used for the MANA conversion are shown in Tables 2 and 3. OPFOR agents remained static with the exception of suicide bombers who moved towards EXFOR infantry elements. Civilian movement was modelled as described in the CAEn scenario overview above however there was no chance that EXFOR entities would accidentally mistake a civilian for an OPFOR entity (as was the case in the CAEn study). Some of these aspects associated with civilian behaviour can be explored in MANA but were not considered for this study.

Table 2. MANA OPFOR ORBAT

OPFOR	Number
Rifles	14
Light Machine Guns	7
Heavy Machine Guns	1
Suicide Bombers	4
Anti-air weapon	1
Grenadier	2
RPGs	4
Sniper Rifle	1
IED	1

Table 3. MANA EXFOR ORBAT

EXFOR	Number
Mortars	6
UAVs	2
IFVs	5
Tanks	2
Rifles	18
Grenadiers	6

Table 4. OPFOR weapons and targets

EXFOR Target / OPFOR Weapon	Infantry	IFVs	Tanks	UAVs	Small UGVs	Large UGVs
Rifle	✓	×	×	×	✓	×
Machine Gun	✓	×	×	×	✓	×
Grenadier	✓	×	×	×	✓	×
Suicide bomb	✓	✓	✓	×	×	✓
IED	✓	✓	✓	×	×	✓
RPG	×	✓	✓	×	×	✓
Anti-air	×	×	×	✓	×	×

Simple rules of engagement also had to be implemented in MANA. This was done by using data from the CAEn wargames in conjunction with additional input from military subject matter experts. By default MANA agents will fire at any visible enemies within weapon range which can lead to a higher than desirable number of unintended firing events. The data collected was used to restrict OPFOR to only target certain EXFOR entities (Table 4). As OPFOR did not have any vehicles there were no restrictions on EXFOR targeting except that the indirect fire could only be employed based on information provided by UAVs and UGVs. Two further changes were forced as a result of the lower fidelity of MANA. These changes provide a good illustration of the type of detail that ABDs like MANA deliberately ignore. The first relates to vehicle vulnerability. In CAEn and other high-fidelity simulations the angle of impact is considered when assessing vehicle damage while in MANA the angle of impact does not affect the probability of kill (P_k). The second forced change relates to the modelling of High Explosive (HE) weapons. The CAEn HE model considers both the dispersion of the weapon round from its targeted location and the blast effect of the weapon on impact. The P_k associated with the blast effect decreases radially from the blast location and is also affected by the terrain. MANA HE weapons model a similar blast effect but the dispersion is not modelled so a HE round will always hit its targeted location and terrain will not alter P_k values [3]. As a result an increase in lethality of MANA HE weapons compared to those in CAEn was expected. There were no significant limitations with the conversion of CAEn direct fire weapon data into MANA.

The final modifications in the conversion process were deliberate fidelity choices made by the authors. As discussed earlier, the use of ABDs often requires a subjective assessment as to the level of fidelity required to represent the key components of a scenario. In this study posture changes by dismounted soldiers were not modelled and all weapon data assumes that both firer and target are standing and stationary. All land based entities were given identical sensors that enabled an entity to instantaneously classify all other entities in line of sight within a given radius. Finally, the only terrain feature modelled in MANA was building walls, which affect both entity movement and line of sight and provide protection from direct fire weapons.

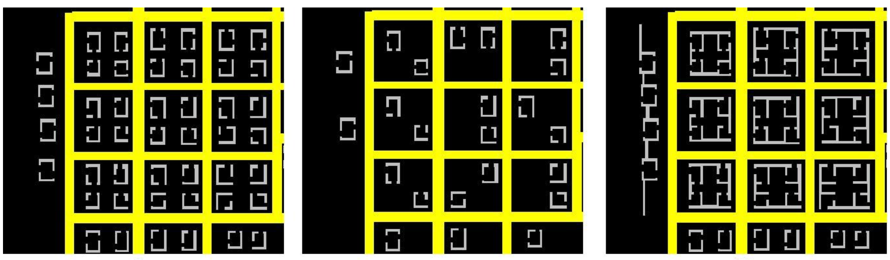
3.2. Data Farming

A baseline scenario set was created in MANA comprising of all ten scenarios from the CAEn study (Table 1). Five additional scenario sets were created to explore different combinations of terrain density and initial OPFOR placement, something not cannot be done in the same timeframe in higher fidelity simulations (Table 5). The first placement option positioned OPFOR entities at random locations within EXFOR's clearance area in order to obtain a baseline for which to compare against additional placement options. As a result some OPFOR entities were placed in relatively concealed locations such as in, or between, buildings while others were in open areas. A second placement option ensured that all OPFOR entities were placed inside random buildings within the EXFOR clearance area. The first terrain option mirrored the building locations of the CAEn study. Two additional terrain types were also modelled. A lower density option contained half as many buildings within the EXFOR clearance area while a third option increased the density of the buildings so that a larger proportion of EXFOR's clearance area was occupied by buildings (Figure 1). This gave a total of 60 scenarios, each of which was run 1000 times in order to obtain a suitable sample for statistical comparisons.

Table 5. Scenario alternatives for OPFOR placement and terrain density

Scenario Set	OPFOR Placement	Terrain
Baseline	Random	CAEn Baseline
Alternative 1	Inside buildings	CAEn Baseline
Alternative 2	Random	Lower Density
Alternative 3	Inside buildings	Lower Density
Alternative 4	Random	Higher Density
Alternative 5	Inside buildings	Higher Density

The second stage of the data farming explored some of the potential unknowns often associated with the size and strength of an OPFOR. A single scenario from the baseline set (B2) was chosen and the number of entities for each element in the OPFOR ORBAT was doubled increasing the total number of OPFOR entities from 35 to 70. The aim was then to create additional scenarios which contained between 35 and 70 OPFOR entities with various weapon combinations. A full factorial based design for this parameter space would result in 345,598 additional OPFOR ORBATs. Instead a nearly-orthogonal Latin hypercube design (Cioppa and Lucas, 2007) was employed which reduced this to 33 additional scenarios which were evenly distributed across the parameter space.



(i) **(ii)** **(iii)**

Figure 1. Terrain density: (i) Baseline, (ii) Lower Density and (iii) Higher Density.

4. RESULTS

4.1. Comparison with CAEn Study

As was the case in the CAEn study, the results for the MANA replications of the same six scenarios also produced non-normal distributions[4] for each of the metrics. Hence, a Kruskal-Wallis test was used to determine the statistical significance of differences across each scenario[5]. The comparisons made between the CAEn and MANA results consider the relative rankings for EXFOR, OPFOR and civilian casualties[6] (Table 6). The different shadings and groupings in each column indicate statistically significant differences for that metric; the highest ranking result (from the perspective of EXFOR) is at the top of each table. For example, Table 6 indicates that for the CAEn study scenario C2 had the fewest EXFOR casualties, B3 the next fewest while B2 and B1 showed no significant difference in the number of EXFOR casualties. As discussed earlier, the intent was not to try and reproduce identical casualty data but to see trends consistent with the CAEn study. No statistical comparisons were conducted between the two models for this reason; therefore the shadings should only be considered in relation to other entries in the same column. A review of the remaining EXFOR casualty data showed that the MANA study produced similar trends to the CAEn study. There were slight differences in the rankings of option B3 relative to B1 and B2 and also A2 relative to the Baseline. Both these differences can likely be attributed to the increased lethality of the way the HE weapons were represented in MANA. EXFOR vehicle options 1 and 2 both had an HE weapon that was not available in the other options and therefore was expected to perform slightly better in the MANA study. Similar trends in both studies were also seen in the rankings for OPFOR casualties. The most noticeable difference was that the C2 option outperformed option B2. The reason for this was likely as a result of the SoM issues discussed earlier, in this case in relation to how the heavy UGV was utilised in the two studies. The trends for the rankings relating to civilian casualties were where the most discrepancies between the two studies occurred. The primary reason for this relates to the modelling of the indirect fire support for EXFOR. As discussed earlier, in the MANA study the indirect fire support relied entirely on information provided by unmanned vehicles. While this helped prevent indirect fire from landing near friendly entities it also meant that significantly fewer mortar rounds were used in the A2 and Baseline options. Given that HE blast effects was the primary cause of civilian casualties in the MANA implementation of the model it comes as no surprise that the number of civilian casualties in the MANA model increases as the level of unmanned vehicles and subsequent calls for mortar fire increases. Triggers for indirect fire support in the CAEn study were based on timings and orders generated during the human-in-the-loop wargaming component of the study. Subsequently the amount of indirect fire in the CAEn study was not related to the number of unmanned vehicles available.

Table 6. CAEn and MANA casualty rankings

EXFOR Casualties		OPFOR Casualties		Civilian Casualties	
CAEn	**MANA**	**CAEn**	**MANA**	**CAEn**	**MANA**
C2	C2	B2	C2	B1	A2
B3	B3	C2	B2	B3	Base
B2	B2	B1	B1	Base	B1
B1	B1	A2	A2	C2	B2
A2	A2	B3	B3	B2	B3
Base	Base	Base	Base	A2	C2

While we have noted that a key requirement for ABDs is to be able to replicate the same trends shown by higher fidelity models it is pertinent to note that in this study the absolute values were also similar for both OPFOR and EXFOR casualties. In the case of civilian casualties there were, on average, approximately half as many in the MANA study when compared to the CAEn study, which is an expected result given the discussions above regarding the modelling of civilians.

It should also be noted that some of the differences between the results of the two models may be influenced by limitations associated with the CAEn study. For each scenario, every replication in the closed-loop CAEn simulations used the same initial locations and SoM for all entities based on data generated from a single wargame[7]. There is a risk that these wargames may have captured outliers, particularly in relation to OPFOR actions.

In terms of computational time, a typical CAEn scenario required roughly one hour to complete a single replication while the same scenario in MANA study could be run over 100 times in the same time frame.

[4] A Shapiro-Wilk normality test with an alpha value of 0.05 was used.
[5] All subsequent MANA results used the same statistical test with an alpha value of 0.05.
[6] The casualty data only considers human casualties and does not include any vehicle losses.
[7] Recent studies adopt a different process that explores multiple OPFOR and EXFOR SoMs for each scenario.

4.2. Data Farming Results

Through providing an overview of the results generated during the data farming component of the MANA study we aim to demonstrate the types of insights that can be rapidly generated using ABDs. We extend the analysis of the MANA study conducted above to include the remaining EXFOR options for the baseline scenario set and compare them to the additional five alternatives. Initially we group the results for EXFOR casualties based on statistical significance (Figure 2). For example, we can see that for the baseline scenario the best performing options (i.e. fewest EXFOR casualties) were C1 and C2 followed by C3, while there were no significant differences between any of the B options. Overall the order of the rankings remained relatively constant despite the changes in terrain and OPFOR positioning with the exception of two cases. In these two cases a shift in the rankings of more than two positions relative to other options was observed. The first case was that option C3 performed better than both B2 and C1 in Alternative 5 (OPFOR in buildings and higher density terrain). These results appear to suggest that the combination of additional firepower and SA provided by the heavy UGV and added EXFOR vehicle protection provided a unique advantage when EXFOR was faced with more complex buildings and an OPFOR that remained in those buildings. The second case occurred in Alternative 1 (OPFOR in buildings, baseline terrain) where B3 performed worse than both A1 and A2. The explanation for this result relates to the relative ability of EXFOR to detect OPFOR entities when they are located inside buildings combined with the lack of a HE weapon for IFVs in Option 3 (discussed earlier). The baseline terrain presented a unique case where only a limited number of OPFOR detections were made by IFVs and so the value of a HE weapon in causing damage to other nearby OPFOR entities was significant. As a result there was less of a threat from OPFOR when the infantry arrived to clear each building which in turn led to fewer EXFOR casualties. In the lower density terrain the IFVs had greater visibility inside buildings and so the utility of possessing a HE weapon was reduced. In contrast there were almost no OPFOR detections by IFVs in the higher density terrain and so weapon type played a minor role. This effect was not as significant for alternatives where OPFOR were randomly placed (Base, Alt2, Alt4) because a much small percentage of OPFOR were located inside buildings. The same effect was not as significant for C3 because the heavy UGV also had a HE capability while the absolute values (not shown) indicated a similar drop off for A3. The two differences identified here provide a useful example of the utility of operational synthesis not only for post-wargaming analysis but also as a technique for identifying potential outliers and areas of interest for high-fidelity models to explore further.

A similar analysis of the civilian casualty data showed no significant changes when compared with the baseline scenario. In the case of the OPFOR casualty data there were some changes to the rankings when comparing across all alternatives. However these differences related only to the number of OPFOR entities remaining outside of the EXFOR clearance area. EXFOR were successful in clearing the designated area in all scenarios. Analysis of the vehicle casualty data showed trends consistent with the CAEn study, namely decreasing vehicle casualties as the level of protection increased.

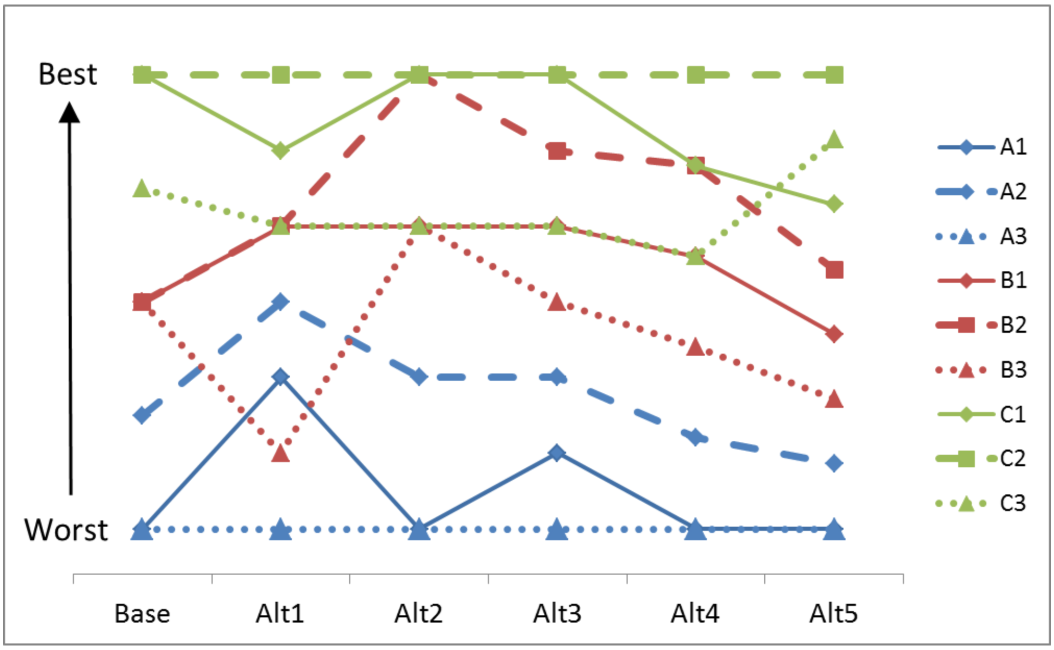


Figure 2. Rankings for EXFOR Casualties

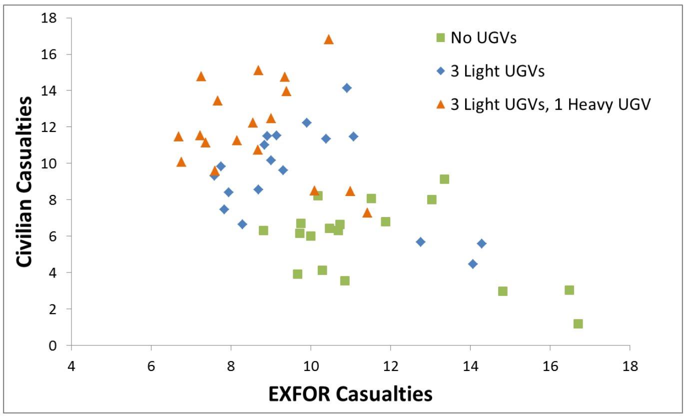


Figure 3. Comparison of unmanned options

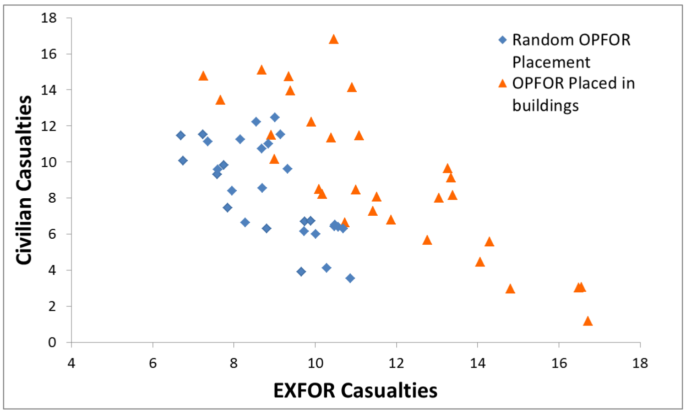


Figure 4. Comparison of OPFOR placement

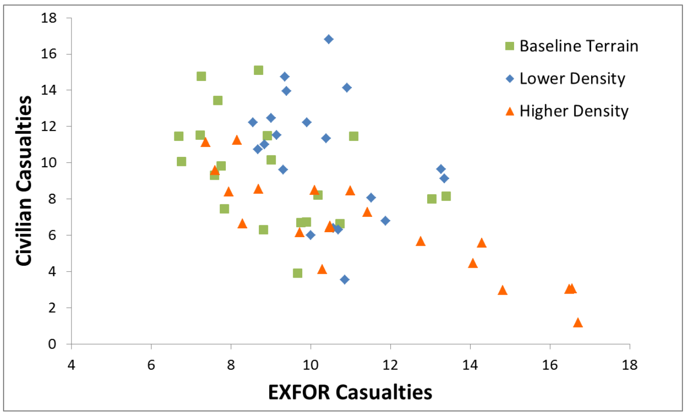


Figure 5. Comparison of terrain variations

Further analysis of Figure 2 shows that when protection levels were held constant the Heavy UGV (Option C) was never outperformed by the other UGV options while having three light UGVs (Option B) was always better than not having any UGVs at all (Option A). We now consider the results from the same set of scenarios from Figure 2 in terms of mean EXFOR and civilian casualties[8]. Figure 3 groups this data by UGV option and suggests that while additional UGV assets improved EXFOR survivability there was also an increase in civilian casualties. This result needs to be considered in terms of how the model represented the utility of the UGVs which in this case was through direct calls for indirect fire regardless of the level of civilian activity in the area. In reality there would be additional decision points between those two events which may lead to a reduction in the use of indirect fire. This effect needs to be explored further.

The placement of OPFOR inside buildings also had a significant effect on casualties (Figure 4) while a slightly counter-intuitive result was observed for the higher density terrain option where there were fewer civilian casualties in some cases (Figure 5). This result can partly be explained by the fact that there was no opportunity in the MANA study for EXFOR to place indirect fire into areas unless OPFOR entities were detected. However, when combined with the previous result (Figure 4) there is an implication that the ability for OPFOR to utilise the terrain (e.g. staying inside buildings) has a significant impact on civilian and EXFOR casualties regardless of terrain density.

The final results we will discuss consider the effect of changing the OPFOR ORBAT (Figure 6). While the distribution of the results is somewhat intuitive, additional insights can be generated by considering which OPFOR assets contribute the most to the relevant measure. In the case of EXFOR casualties the number of suicide bombers produced the best split in the data, as shown in Figure 6. A similar analysis indicated that the overall number of OPFOR entities, regardless of type, had the most influence on civilian casualties.

[8] For legibility reasons Kruskal-Wallis comparisons are not included on Figures 3 – 6. As an indication, for figures 3-5 there are 17 different significant groups for EXFOR casualties and 24 for civilians. In Figure 6 there are 12 groupings for both EXFOR and civilian casualties.

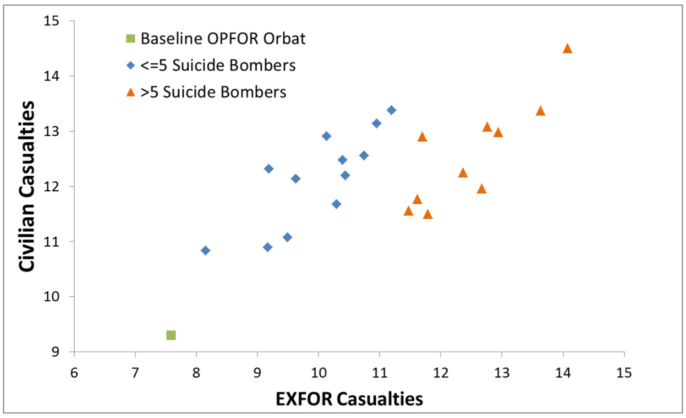


Figure 6. Comparison of OPFOR ORBAT options

5. CONCLUSION

We have demonstrated the potential for ABDs to be integrated with higher fidelity wargaming and closed-loop simulation tools as part of an operational synthesis approach. In particular, for the study explored in this paper, we have established that the MANA model can produce results consistent with the higher fidelity CAEn model while requiring significantly less computational effort and human in the loop input. The reduced fidelity of acquisition and engagement functions and simplified terrain representations that are utilised by MANA and other ABDs enable these efficiency advantages to be achieved.

In the context of this specific study we have also shown how MANA can be used to explore the effect of variations to the size and composition of military forces and the nature of the physical terrain. The results suggest that additional unmanned assets provide greater force protection in all three of the terrain densities used in this study. In addition, a significant variation in the number of EXFOR and civilian casualties was noted when OPFOR were positioned inside buildings which suggests that further studies should be conducted to explore the effect that multiple SoM variations for each side has on the outcome.

Further work is also required to investigate the level of fidelity required for a distilled model to consistently replicate trends shown in higher fidelity models or historical studies. This work should consider additional terrain features and their impact on entity mobility and the level of cover and concealment provided.

The findings of this paper highlight the potential for ABDs such as MANA to complement the suite of analytical tools currently used to support military decision making. This suite of tools is often used to inform military clients on issues such as acquisition, force structure and doctrine development. The ability for ABDs to explore vast parameter spaces in a relatively short period of time could be exploited to provide initial insights during the problem definition and design stages of these military studies and also to add robustness during the analysis phase.

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