A Concept for the Modelling and Simulation of Complex Urban Environments

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ABSTRACT

The urban environment provides challenges for military forces such as complex physical terrain; a population of significant size and density; multi-dimensional infrastructure and transportation systems; and complex communication and information systems. To prepare future forces for these complex environments, it is critical that they are accurately represented in future training systems, due to limitations in live training ("the Real World") such as scale, complexity and cost.

The Defence Science & Technology Laboratory (Dstl) has researched methods of understanding, modelling, and simulating the complexity of the urban environment to increase the effectiveness of the next generation of military training systems. Analysis of existing models and frameworks against anticipated training requirements has concluded that a single simulation approach is impractical.

A proposed solution is a 4-tier urban simulation architecture that combines virtual simulation, with constructive simulation to model Political, Military, Economic, Social, Information, Infrastructure, Physical environment, and Time (PMESII-PT) effects. Each tier operates at a different level of geographical abstraction and temporal activity, allowing a more efficient use of computing resources.

This paper describes the core architecture, information flows, and efforts towards building a technical demonstrator to support UK military training and force development activities.

1. INTRODUCTION

Traditionally, conflict has been fought for and amongst the civil population, either to capture strategic territory or to force political aims. The siege and capture of key cities and towns has been an integral part of military operations throughout history and are considered a key objective [1]. Urban territory is usually located alongside key lines of communication and fortified garrisons located within these areas could act as a reservoir of military forces to threaten an oppositional advance [2].

The introduction of large nation states and industrialised armies changed this balance by allowing significant military forces to be sustained in the field, capable of isolating and bypassing all but the largest settlements, thus relegating urban operations to a battle of choice. Over time, industrialised militaries became optimised towards long range engagements and high tempo operations sustained by small groups of highly trained, professional forces. International law highlighted the protection of non-combatants and the civil population. A combination of these factors has led to a reluctance by modern western forces to engage in sustained urban operations.

This balance of risk is changing. In Out of the Mountains [3], David Kilcullen argues that urban warfare is unlikely to constitute the exception and instead will be the norm in future operations.

"Wars happen where people live, and people will be overwhelmingly concentrated in coastal cities"

The World Urbanzation Project states that 55% of the global population currently lives in urban areas and by 2050 the proportion is expected to reach 68% [4]. Approximately 90% of this increase in urbanisation is expected to happen in developing countries such as sub-Saharan Africa and Asia, where the local political climate is already fragile. By 2030 it is projected that there will be 43 megacities (cities with more than 10 million inhabitants). Due to the benefits of having access to national and international water-based trade routes, much of this growth will be in littoral cities. This trend of rapid global urbanisation, combined with the desire of potential adversaries to negate the perceived strengths of modern military forces will result in a greater risk of large-scale urban conflict.

Furthermore, it is evident to NATO forces that the re-emergence of urban warfare in the context of the Future Operating Environment (FOE) will present numerous challenges:

"*For our Armed Forces, the urban environment will be one of the most challenging areas to operate in. The city, and its surrounds, will become an increasingly complex and ambiguous tapestry of multiple actors with shifting allegiances, in which we may be required to operate in a variety of ways, from major conflict at range to peace support and humanitarian operations."[5]*

The reality that future operations are predominantly going to happen within an urban environment means that it is imperative that our Armed Forces are prepared to operate in these complex environments. The purpose of this paper is to present recent efforts into analysing urban training requirements and identifying opportunities for simulation to enhance current and future urban training.

2. THE CHALLENGE OF THE URBAN ENVIRONMENT

2.1. Nature of Urban Environments

Urban environments can range from a small collection of temporary structures, through long established towns, to the rapidly growing megacities of the 21st century. They are characterised by a dense array of populated artificial structures which produce a contested environment with a constrained ability to manoeuvre, resulting in a challenging operating environment for military forces [6].

Complex urban environments, especially cities, can be understood as an adaptive system-of-systems, comprising a complex physical terrain with an underlying infrastructure and a human population [7]. Each of these systems is interconnected and characterised by a dense and constant flow of people, information, and services. Since these systems are more closely coupled in a city than in a rural environment, any military activity has a greater chance of resulting in significant collateral damage. The increasing interconnectedness of cities also means that local actions that disrupt the flow of goods and services in one city could potentially result in global consequences. However, due to the importance of preventing civilian casualties and adhering to the International Humanitarian Law (IHL), the main challenge to military operations is the density of the human population present in the battlespace [8].

The increased scale of urban environments brings unique challenges for the military planner. Most military forces can no longer envelop and isolate all but the smallest urban conglomeration. Instead, they must traverse through, and operate within urban spaces. Whilst the difficulties of operating in an urban terrain remain constant, large settlements, especially cities, can quickly overwhelm the command and control of current military forces. The man-made terrain[1] in urban environments significantly limits the ability of troops to manoeuvre and hinders situational awareness, constraining their constraining their ability to coordinate fires and provide mutual support when compared to open terrain. The emerging megacities, with their complex economic and social structures, may provide unique planning challenges.

In 2020, the Defence Science and Technology Laboratory (Dstl) published a report [10] which identified implications of the urban environment for our Armed Forces which in turn helps identify what may need to be included in future training systems:

- Congested transport routes will put a strain on the ability of combat units to manoeuvre and resupply.
- The increasing prevalence of smart cities means that it will no longer be sufficient for the military to focus only on kinetic activities during urban operations. It is important that personnel learn to exploit the cyber and cognitive opportunities presented by the virtual linkages found in smart cities.
- Increasing demographic diversity means that there will be a wide range of cultural groups with differing patterns of behaviour. This makes it increasingly important to train personnel in cultural understanding and language capabilities.

[1] The urban terrain is not only characterised by a higher density of buildings, it also presents significant verticality with tall buildings and subterranean spaces

- As smart Internet of Things technologies become ubiquitous, these will present opportunities for exploitation and for overcoming some of the hindrances introduced by the urban environment. The vast amount of data produced by a smart city, and the rapid update rate, could help increase situational awareness by using it for Intelligence, Surveillance and Reconnaissance (ISR) and tracking of persons of interest. For humanitarian operations, these can be used to improve the distribution of aid.

In summary, urban operations do not only place a high physical demand on troops, having to navigate and conduct activities in an increasingly challenging environment, but also create a high cognitive demand. Military forces must consider the higher order consequences of their actions through a thorough understanding of the system-of-systems that is the urban environment.

2.2. Urban Environment Training Challenges

It is evident from the above discussion that urban environments present significant challenges that are not prevalent in other operating environments. It is also clear that operating in an urban environment is no longer a question of if, it is a matter of when.

The UK Future Force Concept [11] states:

"To succeed in urban operations our forces will require access to the different variety of urban terrain types to allow realistic training and experimentation. The use of augmented reality and virtual systems should support training to deal with the challenges representing the scale and complexity of urban operations."

This was further reinforced by the Commander of the [British] Field Army who has stated that 50% of all training must have an urban focus [12].

However, whilst this shows top level recognition of the importance of urban training, it is not enough to simply increase the proportion of current urban training. The reality is that the historical focus on urban training has been on offensive or defensive combat operations with an emphasis on close quarter battle and house clearance. This biases training towards a bottom-up process whereby section level drills are combined up to company level activity with limited combined arms contributions and almost no representation of higher echelon support or joint enablers.

This has meant a focus on the physical dimension and, even then, at a scale and density that does not sufficiently represent the scope of the urban problem. Developments in recent years[2] have significantly improved training estates, offering more realistic environments as the need to train for urban operations becomes a necessity rather than merely desirable. However, the complexity of the environment and rapid developments in tactics, equipment, technology, adversary behaviour and the resiliency of urban populations continues to outpace improvement in training real estate, with a widening gap between what can be represented in live training and the experience of real urban operations. In effect, the current approach to urban training has now reached the limit of what 'live' training can represent. The only realistic and viable option now being to broaden, develop and better integrate the use of M&S to fill the gap.

Understanding of the urban system can be visualised through the Interconnected Landscape Model **Figure 1**, as identified and utilised during NATO research into future urban operations [14]. The

[2] For example, the US National Training Centre, includes the city of 'Razish' with different types of urban environment and terrain, including over 600 buildings. This facility allows for up to Brigade Combat Team training. [13]

framework consists of a complex man-made *physical* terrain; a *social system* consisting of a population of significant size and density with varying sociocultural groupings; multi-dimensional city infrastructure & transportation; and the *informational* connectedness of the city. The Interconnected Landscape Model with its associated dynamics and flows, represents those core elements that must be understood to enable effective functionality and operations within an urban environment.

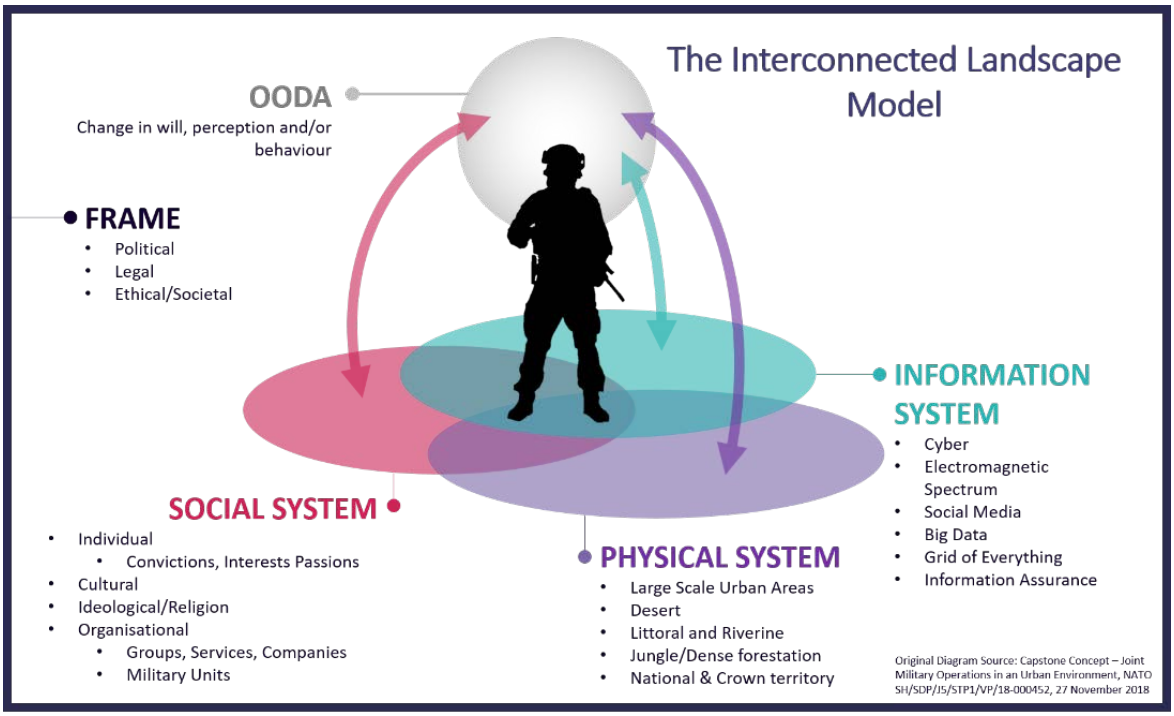

Figure 1: The Interconnected Landscape Model

A 2020 Dstl commissioned study [15] combined the understanding of the urban landscape with an analysis of historic[3] and more recent[4] examples of urban operations to derive key focus areas for future training systems. These were grouped into several themes outlined below:

- **Decision Making:** Due to the complexity of the environment, tactical decision making will have to be decentralised and delegated. Training should represent these effects and key decisions may be cascaded all the way down to the lower tactical levels (section to company).

- **Comprehensive Urban Threats:** Large urban areas often favour the defender and attacking units will face a broad range of conventional and irregular threats in these environments.

- **Disrupted & Denied Communications:** The dense urban and electromagnetic environment will cause significant disruptions to the ability of units to communicate.

- **Contested Electromagnetic Environment:** The ubiquity of Information and Communications Technology (ICT) in urban environments presents both challenges and opportunities for information manoeuvre and intelligence gathering by the military – i.e., Cyber and Electromagnetic Activities (CEMA), Electronic Warfare (EW), and Influence Ops. It is also likely that these will be exploited by adversaries.

- **Critical Infrastructure:** Infrastructure networks are vital for the functioning of a city. Planners must be able to identify and correctly devise a course of action around the protection of critical infrastructure nodes and hubs to minimise the impact of military activities.

- **Logistics & Sustainment:** Urban operations are particularly demanding in terms of sustainment, and logistic dominance is key. It is important that key logistic data and sustainment loads be represented in training.

- **Human Behaviour Representation:** The human dimension cannot be separated from the physical environment. The significant size and density of the population in these environments means that any military activity must be carefully planned and conducted to minimise the potential for collateral damage. It is important to represent this at tactical as well as operational and strategic levels.

With an understanding of the urban training requirement, the current training capabilities, predominantly configured for small scale 'Fighting in Built Up Areas' (FIBUA), have significant gaps in their ability to fully prepare personnel for the scale of modern urban warfare. These facilities do not realistically mirror the nature of contemporary or future urban environments. Their limited size and inability to represent the full scale of operations (indirect fires, certain platforms, destructive effects etc.) means that they are most effective for Close Combat Battle drills and cannot effectively support combined arms training. It is important that units are exposed to frictions that mirror those they will face in a real-world operational environment. This will allow them to develop resilience and practice the skills to perform effectively under these stressful conditions.

[3] Stalingrad (1942-43), Aachen (1944), Algiers (1956-57) & Grozny (1994-2000)

[4] Sadr City (2008), Mosul (2016-2017) & Marawi (2017)

3. THE ROLE OF SIMULATION IN ADDRESSING GAPS IN URBAN TRAINING

Many of the gaps identified in the current training estate can be addressed by employing simulation to augment live training, or to provide a fully synthetic alternative where this is not available or feasible.

There are several noteworthy urban models and simulations including:

- The NATO Modelling and Simulation Centre of Excellence (MSCOE) Archaria Model & the Netherlands Organisation for Applied Scientific Research (TNO) MARVEL model was used during the NATO Urbanisation Project Wargames for visualisation and for identifying second and third order effects of military actions in an urban environment respectively [16];

- The US Army Solago Urban Model used during the U.S Army Subterranean and Dense Urban Environment Materiel Developer Community of Practice table top exercises [17];

- Dstl's Close Action Environment model (CAEn) is an interactive, multi-sided stochastic wargame and simulation specialised in urban combat which is used to model forces up to Company level. [18];

- Matrix Games Combat Mission is a 3D, turn based, tactical wargame using a 'We Go'[5] system. Combat Mission enables urban wargame focused on the physical urban environment up to Company level [19].

Many existing models have been developed with wargames in mind and therefore the integration of credible urban modelling and simulation with live urban training is limited.

There remains a challenge to provide real time urban simulations at the tactical level to support the development of cognitive skills at the team and collective training with distinct gaps in representing population and combat behaviours, weapon effects on building and terrain, cyber and electronic warfare. Additionally, there is a lack of adequate constructive models to support staff C2 and planning training at battalion and above.

A follow on 2021 Dstl commissioned study sought to identify the M&S requirements which would enable M&S to augment appropriate shortfalls in M&S [20]. By using the Interconnected Landscape Model in conjunction with the urban training NATO Standardization Agreement (STANAG) ATrainP-3 [21] and the type of operations being trained for, the elements that need to be represented within an urban training environment, through live training and/or simulation, can be identified.

[5] A 'We Go' System is where both sides enter their orders and then the simulation executes them simultaneously so it give realistic results.

The ATrainP-3 categorises urban training requirements into three levels: basic (individual), basic branch (specialist), and collective (Combined Arms and Joint). Several key examples are presented below:

Physical

- Better representation of the effects of direct and indirect fire weapon systems on the physical environment, either entirely within a simulated environment or blended with live environments potentially using Augmented Reality (AR)/Virtual Reality (VR) or other technologies where appropriate.
- Accurate representation of Critical Infrastructure (i.e., power, water, sewerage) and the impact this has on the civil population when they are destroyed or damaged.
- Better representation of urban adversaries and threats to simulate the 360-degree urban threat environment.

Information

- Simulation of the data that will be available at different levels of training. Use simulation to introduce effects of new technologies or allow the use of those that are data dependent, i.e., for CEMA, EW, and influence activity.

Societal

- Address the need for situational awareness training, including situation recognition based on patterns of life and agent behaviours.
- At the collective level, represent the effects of influence activity on civilian behaviour.
- Represent the consequences of full spectrum operations on the population.

Understanding/Cognitive Domain

- Provide urban information feeds needed to enable training of non-combat elements, such as indirect fires, targeting, intelligence and logistics.
- Represent the realities of urban terrain and urban combat to help familiarise forces.

4. URBAN SIMULATION CONCEPT

It is impractical to construct an entire virtual city to the level of detail required to represent full spectrum military operations and effects. Instead, the urban environment needs to be subdivided to allow detail to be concentrated where it is required across both the levels of training (as categorised by ATrainP3) and the complexity of the urban environment (as categorised by the 'Interconnected Landscape Model).

The urban simulation model concept proposed in this paper provides a method of achieving this effect.

4.1 Functional Tiers

The proposed urban training framework is divided into four discrete simulation layers as shown in **Figure 2**:

- Inner Tactical Zone (ITZ)
- Outer Tactical Zone (OTZ)
- City Region Zone (CRZ)
- World Zone / Global Informational Zone (GIZ)

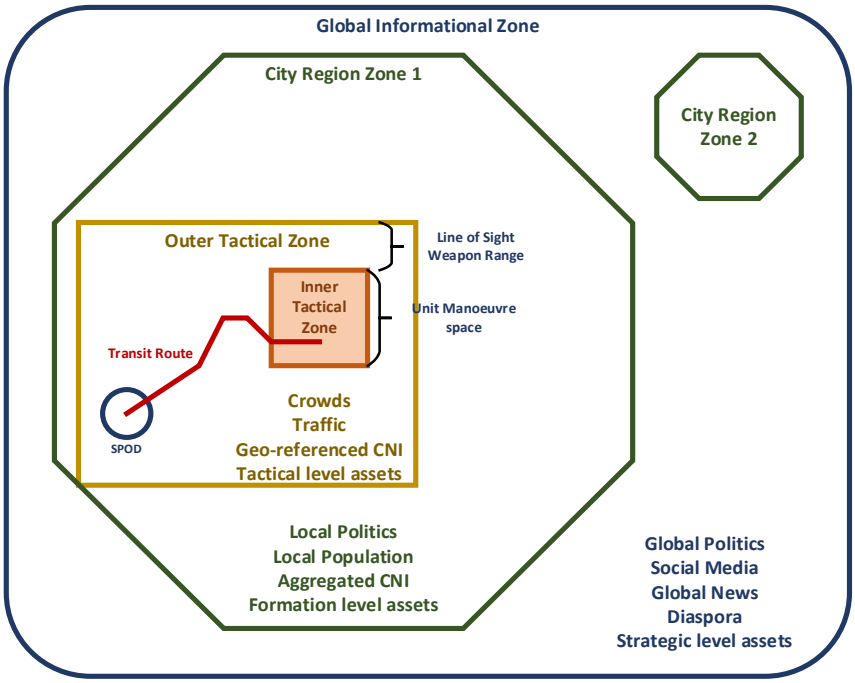

Figure 2: 4-Tier Model

Inner Tactical Zone (ITZ). This is a highly detailed simulation area used to represent mounted and dismounted tactical combat operations and is optimised towards the requirements of individual and small unit collective training events. Often viewed from a first-person perspective, it operates in 'real-time' where one second of simulation time represents one second of time as perceived by the user.

This zone is modelled to high fidelity and includes building interior walls and partitions, complex infrastructure networks (including local power, communications, and services) and a resident population represented as individual agents. Structures inside this zone are enterable by the training audience and so include interior features such as partition walls and doors. It may also include furnishings as appropriate.

High intensity urban combat stresses the use of high explosives, including grenades, field guns and short-range missiles, all of which can cause significant structural damage. Therefore, buildings and objects need to be deformable, realistically representing different construction materials and the effect of many weapon types. Specifically, structures must be breach-able, allowing ad-hoc access routes to be made between different rooms and floors. This will stretch the capabilities of current generation simulation tools.

This zone is scaled to represent the manoeuvre space required by the formation being trained within the allocated period of the training event and would usually encompass a small city block or a residential street. Mapping and constructing an ITZ to the required level of fidelity is a significant undertaking and it is expected that only a small number of these would be created to represent the different types of terrain encountered within an urban environment.

Outer Tactical Zone (OTZ) is a larger, lower fidelity region than the ITZ. It is used to model ingress and egress routes to the ITZ and to provide context for higher formation activity. Buildings are represented at a higher level of abstraction to the ITZ, with interior features limited to floors and heavy structural partitions. Since most of this area will only be observed from a distance or through the windows of a vehicle, a lower quality of building exterior is required when compared to the ITZ.

Critical Infrastructure is represented such that destructive activity within the ITZ may be observed by disruption to 'Pattern of Life' activity in this zone (i.e., changes of human behaviour, interruption of automated systems or power networks). Non-essential elements of the population may be modelled as crowds or aggregated units, allowing the efficient generation of an appropriate 'pattern of life' behaviour. These agents will exhibit fewer complex behaviours than those observed in the ITZ, saving scenario scripting time and computational requirements.

The OTZ must be scaled to allow the placement of friendly and hostile 'non-player' forces which might exert line of sight effects along the transit route and within the objective area (including observation posts, weapons teams and signal re-broadcast assets). It will typically extend more than 1 km either side of the transit route and objective area and so will contain 100s to 1000s of structures. It is likely that a high degree of automation will be used to generate features in the OTZ, and so it will be much less expensive to develop than the ITZ.

This zone runs in real-time and can be represented using current generation entity level simulations.

City Region Zone (CRZ) is used represent the entire urban conurbation[6]. It represents the wider political context that the training serial is taking place under and is the first tier to model the full range of PMESII-PT effects. It is required to provide a 'consequences of actions' mechanism which can evaluate the disruption to infrastructure networks, major population effects (such as political consequences of actions) and hold the location of long-range indirect weapons systems such as artillery.

[6] An extended urban area, typically consisting of several towns merging with the suburbs of a central city.

Since it is not directly perceived by the training audience, this zone can be described using a Geographical Information System (GIS) or constructive type simulation, rather than requiring a 3D rendered environment. It may operate in discrete time steps with minutes or hours of activity processed at a time. If required, 3D views may be generated using procedural terrain generation, rather than the detailed modelling required for the Tactical Zones.

This zone is bounded by political as well as geographic extents and is likely to cover a wide area of 100s of km and include a population in the 100,000s upwards. As such, population behaviours are modelled using highly aggregated models, which in turn will generate consequences over time periods greater than the core simulation engine. Once the core training event has completed, this part of the simulation will continue to run in accelerated time to help generate an after-action review of events.

Global Informational Zone (GIZ) provides the outermost view for the whole operation and is used to connect different city scale models together. This is predominantly an informational environment, although it could be used to store the geographical location of some long distant surveillance and fires systems. Key attributes include the modelling of influence activity including the sentiment and activity of a city's global diaspora. Suitable models may be time step or event driven based as they need to resolve long periods of activity, potentially extending weeks after the end of the training scenario concludes.

4.1 Layers of Abstraction

A modern city can encompass 100,000's of people and 100's of km^2 of terrain, impractical to model in full detail. To aid data acquisition and modelling, the city should be subdivided into smaller geographic blocks, many of which will be modelled at a high level of abstraction. Detail should only be added where it is needed to support training requirements.

Figure 3 shows how a city can be subdivided into segments using existing administrative boundaries. These boundaries often reflect underlying physical or social features within the urban environment and so align with military planning objectives. In this example, Ward F is the location of the contact battle and is modelled at the ITZ level. It is located within District 5 which is used for the OTZ. If required, multiple Wards or Districts can be combined into a single Zone to aid simulation processing.

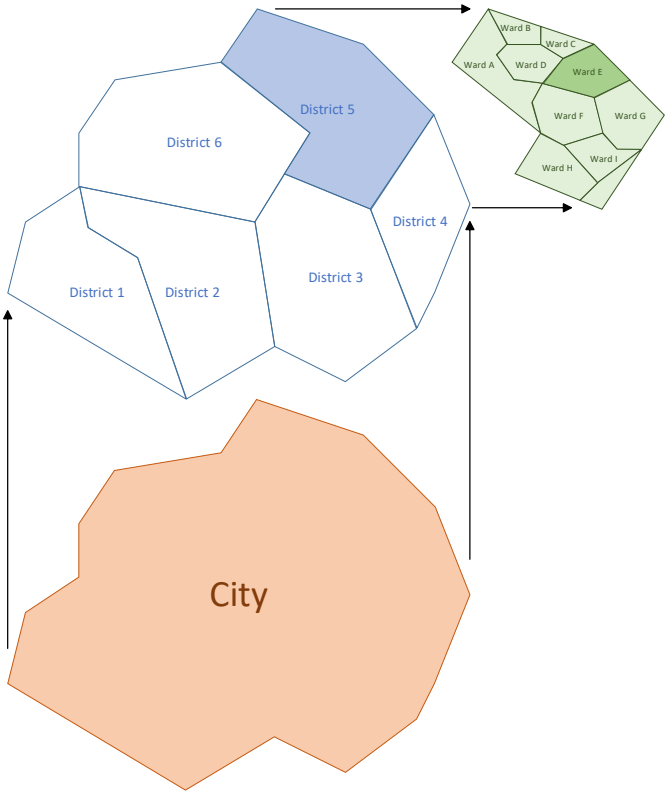

Figure 3: Urban Decomposition into Districts and Wards

Each layer of the model communicates through a standard set of interconnections that represent the flow of services and resources (including people) as shown in **Figure 4**. At each level, city flows are aggregated and split in response to local conditions. This allows multiple instances of each tier to share information and permits different levels of abstraction to be employed for the different regions of the urban area. For instance, a comprehensive model with destructible buildings could be used to represent a critical street that a force is fighting along, and a simplified model with static structures used to determine the consequences of that activity on an adjacent region. This level of composition avoids the need to model the entire city at the highest level of fidelity required to support a specific training serial, significantly reducing computation and data requirements.

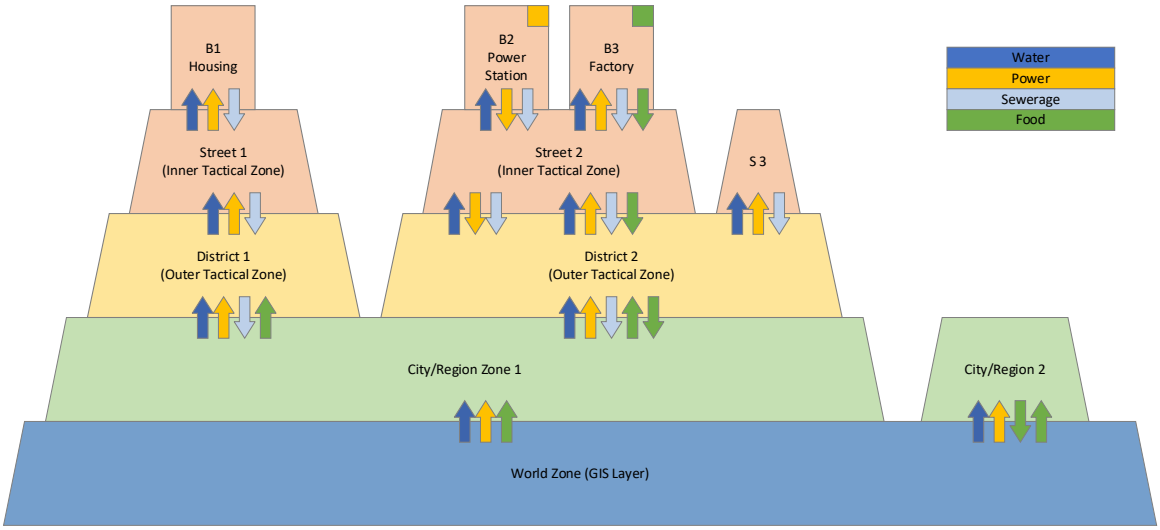

Figure 4: Urban Model Interconnections

4.1 Temporal Abstraction

Lower echelon headquarters (section to company scale forces) are predominantly concerned with the 'current' battle, managing an operation on a minute-by-minute basis. They are usually concerned with short term measurable objectives (i.e., secure a building or patrol a street). Control of a mission may be visual (in the case of a section or platoon), through electronic systems or via radio in the case of a Company HQ. In all cases, the supporting models and simulations must be able to generate information in real-time whilst the training event is in progress. After the event has concluded, it may be advantageous to model the next few hours or days of activity to allow the trainee to understand the full consequences of their decisions and actions.

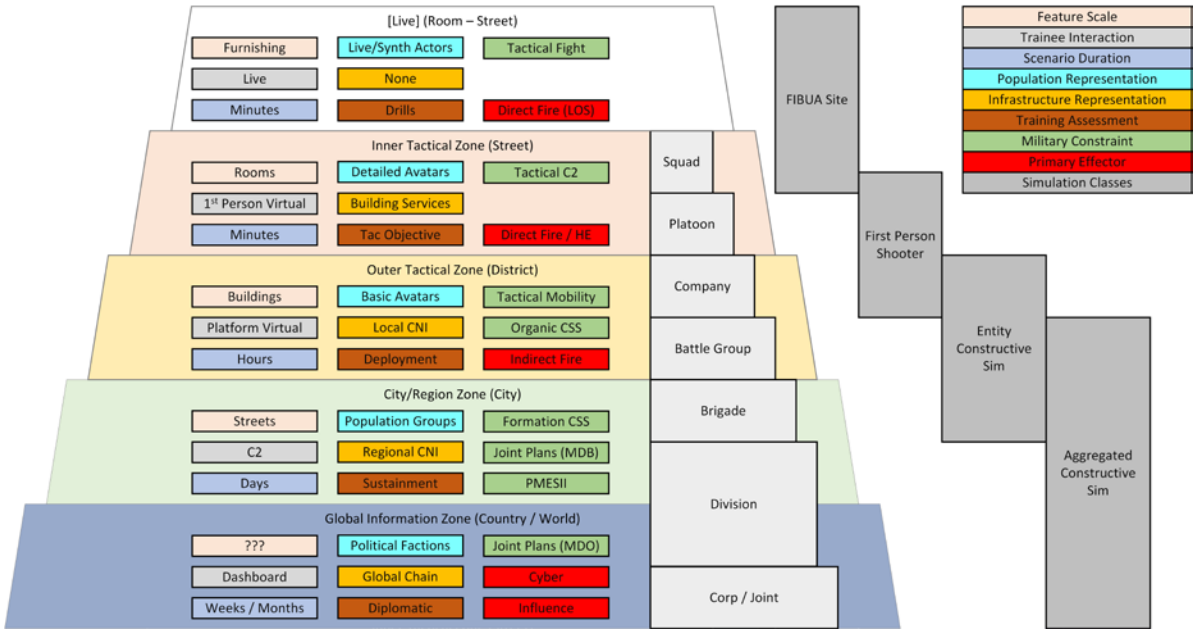

Figure 5: 4-Tier model and intended training activity

5. CONCLUSIONS AND NEXT STEPS

This paper has outlined both the increased relevance and the complex nature of urban operations. It has described some of the challenges that our current training estate faces when delivering urban training at the required scale and complexity, and highlighted an opportunity for M&S to deliver enhanced force preparation. However, we believe that no single model is capable of providing the full spectrum of urban effects, and where models already exist, they have not been designed to fully interoperate with live training or other models as part as a federated synthetic requirement.

Consequently, this paper has presented a concept for the composition of simulations to address differing training requirements, including the differing requirements for physical and temporal abstraction.

Further research commenced in September 2023 to refine a high-level design for an Urban Concept Demonstrator. This is intended for construction by 2025 and will help identify where gaps exist in existing models and concepts, and where additional standards are required to accurately communicate effects across layers.

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