NORTH ATLANTIC TREATY ORGANIZATION

SCIENCE AND TECHNOLOGY ORGANIZATION

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STO TECHNICAL REPORT **TR-MSG-156**

Correlated Dynamic Synthetic Environments for Distributed Simulation

(Environnements synthétiques dynamiques corrélés, destinés à la simulation répartie)

Final Report of NATO MSG-156.

Published October 2021

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The NATO Science and Technology Organization

Science & Technology (S&T) in the NATO context is defined as the selective and rigorous generation and application of state-of-the-art, validated knowledge for defence and security purposes. S&T activities embrace scientific research, technology development, transition, application and field-testing, experimentation and a range of related scientific activities that include systems engineering, operational research and analysis, synthesis, integration and validation of knowledge derived through the scientific method.

In NATO, S&T is addressed using different business models, namely a collaborative business model where NATO provides a forum where NATO Nations and partner Nations elect to use their national resources to define, conduct and promote cooperative research and information exchange, and secondly an in-house delivery business model where S&T activities are conducted in a NATO dedicated executive body, having its own personnel, capabilities and infrastructure.

The mission of the NATO Science & Technology Organization (STO) is to help position the Nations' and NATO's S&T investments as a strategic enabler of the knowledge and technology advantage for the defence and security posture of NATO Nations and partner Nations, by conducting and promoting S&T activities that augment and leverage the capabilities and programmes of the Alliance, of the NATO Nations and the partner Nations, in support of NATO's objectives, and contributing to NATO's ability to enable and influence security and defence related capability development and threat mitigation in NATO Nations and partner Nations, in accordance with NATO policies.

The total spectrum of this collaborative effort is addressed by six Technical Panels who manage a wide range of scientific research activities, a Group specialising in modelling and simulation, plus a Committee dedicated to supporting the information management needs of the organization.

- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS System Analysis and Studies Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These Panels and Group are the power-house of the collaborative model and are made up of national representatives as well as recognised world-class scientists, engineers and information specialists. In addition to providing critical technical oversight, they also provide a communication link to military users and other NATO bodies.

The scientific and technological work is carried out by Technical Teams, created under one or more of these eight bodies, for specific research activities which have a defined duration. These research activities can take a variety of forms, including Task Groups, Workshops, Symposia, Specialists' Meetings, Lecture Series and Technical Courses.

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List of Acronyms

C2	Command and Control
CAS	Close Air Support
CDB	Common DataBase
CGF	Computer Generated Forces
CIGI	Common Image Generator Interface
CM	Conceptual Modelling
DBGS	DataBase Generation System
DIS	Distributed Interactive Simulation
DOF	Degrees of Freedom
DSE	Dynamic Synthetic Environment
DTED	Digital Terrain Elevation Data
ECMWF	European Centre for Medium-Range Weather Forecasts
EDCS	Environmental Data Coding Specification (EDCS) – SEDRIS
EO	Electro Optical
FAC	Forward Air Controller
FACC	Feature and Attribute Coding Catalogue
FOM	Federation Object Model
FTIMS	Federate Terrain Interaction Modification Service
GML	Geography Markup Language
GRIB	GRidded Information in Binary
HLA	High Level Architecture
IED	Improvised Explosive Device
IFV	Infantry Fighting Vehicle
ISA	International Standard Atmosphere
ISR	Intelligence, Surveillance and Reconnaissance
JSON	JavaScript Object Notation
LOD	Levels of Detail
M&S	Modelling and Simulation
METOC	Meteorology and Oceanography
MSaaS	Modelling and Simulation as a Service
MSG	Modelling and Simulation Group
NATO	North Atlantic Treaty Organization
NETCDF	NETwork Common Data Form
NETN	NATO Education and Training Network
NMSG	NATO Modelling and Simulation Group
NMSMP	NATO Modelling and Simulation Master Plan
NMSSP	NATO Modelling and Simulation Standards Profile
NOAA	National Oceanic and Atmospheric Administration
NRMM	NATO Reference Mobility Model

OGC	Open Geospatial Consortium
PDU	Protocol Data Unit
PfP	Partners for Peace
PoW	Program of Work
RCI	Remolded Cone Index
RIEDP	Reuse and Interoperation of Environmental Data and Processes
SCORE	Simulation Composition and Representation of natural and Physical Environments
SE	Synthetic Environment
SEDRIS	Synthetic Environment Data Representation and Interface Specification
SES	Synthetic Environment Service
SISO	Simulation Interoperability Standards Organization
SNE	Synthetic Natural Environment
SOA	Service Oriented Architecture
SPE	Synthetic Physical Environment
STANREC	NATO Standardization Recommendation
TAP	Technical Activity Proposal
TG	Task Group
TIFF	Tagged Image File Format
TRL	Technology Readiness Level
UAS	Unmanned Aerial System
UAV	Unmanned Air Vehicles
VCI	Vehicle Cone Index
WCS	Web Coverage Service
WFS	Web Feature Service
WMS	Web Mapping Service
XML	Extensible Markup Language

Acknowledgements

This final report describes the work of the MSG-156 Task Group and it depicts the work that Task Group members carried out. The group would like to thank all members for their inputs during the meetings, discussions and concept demonstration that was performed. The input of ideas, thoughts and previous national research work by the participating nations all contributed to achieving the TG objectives.

For the concept demonstration, participating nations provided simulation systems and services. These were modified to adhere to the new DSE architecture that MSG-156 has defined, allowing a proof-of-concept demonstration to be made. The task group would like to thank everybody that provided assets and modified them to demonstrate the concept.

Although this final report is the work of the entire TG, the group also wants to thank a few persons or nations especially for their assistance:

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- Boeing Defence UK (BDUK) and Boeing R&D Australia for presenting information about their weather server implementation to the group and joining discussions about dynamic weather.

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Correlated Dynamic Synthetic Environments for Distributed Simulation

(STO-TR-MSG-156)

Executive Summary

The use of Modelling and Simulation (M&S) is an important capability for the NATO alliance and its partner nations for defence joint, collective and coalition training, capability development, mission planning and preparation, and decision support. Defence operational environments are highly dynamic, where the state of the physical environment impacts force behavior (e.g., effects of weather on ground vehicle mobility), and the effects of physical (kinetic) force behavior impacts the state of the environment (e.g., munitions damage to buildings, infrastructure, etc.). Current M&S practices, standards and technologies mainly achieve static representations of the outside world environment in distributed simulations, based on common environmental datasets and by re-using environmental databases. Where dynamic elements are represented in current simulation systems, they are implemented in a way that is often pre-scripted and specific to a given system. This limits the capability and scope for interoperability of distributed heterogeneous simulation systems and impacts the use of M&S for applications such as coalition training, which requires common and consistent representations of operational environments to ensure fair fight conditions.

MSG-156 started in 2017 as a 3-year Task Group (TG) to address the gap between the need to represent the challenges of the real-world operational environments in M&S systems and existing technical capabilities, with the objective to research how a correlated Dynamic Synthetic Environment (DSE) can be represented in future distributed simulations. The TG comprised Subject Matter Experts (SMEs) from government, research institutes and industry across NATO partner nations, including both developers (providers) and consumers (users) of simulation and Synthetic Environments (SEs).

The research activities carried out by the MSG-156 TG will inform one of the key objectives of the NATO M&S Master Plan, i.e., 'Develop a NATO standard interoperability architecture for simulation applications and supporting material'.[1]

After surveying existing capabilities for dynamic environments in simulation systems and investigating state-of-the-art technology and algorithms in simulations and entertainment games, the TG developed conceptual modelling diagrams based on Use Cases to identify the key interactions needed within a DSE environment. Modelling and Simulation as a Service (MSaaS) concepts formed the basis of a conceptual solution architecture for the DSE. The TG studied the specifics of dynamic terrain and realistic weather to refine the conceptual approach into a detailed solution architecture that allows a consistent representation of a dynamic synthetic environment across heterogeneous distributed simulation systems.

The key concept of this solution architecture is that common services are responsible for managing and distributing environmental data within the simulation exercise. This means that M&S federates will use a Terrain Service to obtain information about the terrain and a Weather Service to obtain information about the weather. By having one service responsible for managing this data, many correlation issues can be mitigated. Furthermore, when making dynamic changes to the synthetic representation of the operational environment, a particular, specialized service is responsible for performing the modifications, eliminating

[1] NATO Modelling and Simulation Master Plan, Version 2.0, 14 September 2012, Document AC/323/NMSG(2012)-015.

correlation issues that would occur when such modifications are implemented locally in each individual system. These data modification services communicate their changes to the Terrain Service, allowing all federates to access the updated data from there.

Following development of the DSE conceptual architecture, MSG-156 performed a proof-of-concept demonstration where federate simulations and services provided by the participating nations using tools and products supplied by different industrial partners were deployed, integrated, and executed using this architecture. Although the number of federate simulations and services available was limited in number, the demonstration has proven that the solution architecture is feasible and that such an architecture will help in ensuring that dynamic changes can be made and represented in a consistent way across distributed simulations. The concept demonstration has also helped to identify which aspects of the architecture need further research to reach a Technology Readiness Level (TRL) to support operational simulation exercises.

Due to the limitations of time and scale, the technology used in the proposed MSaaS-based DSE architecture is currently not proven to be mature enough to be implemented into operational simulation systems. The Task Group therefore recommends that a larger scale experiment should be carried out to evaluate how the solution architecture will perform in an environment where the services are stressed in a more realistic test case.

The DSE architecture depends on having standardized interfaces between the different services. Although some of these interfaces are already mature, for example the OGC interfaces to distribute geographical information, other interfaces will need to be considered for further development as part of being taken forward as future open standards. Furthermore, options for a new format should be explored for sharing 3D content which supports the distribution and streaming of 3D model content to simulation systems, or for making dynamic changes to 3D model content during simulation execution time.

Acquisition of real-world weather data proved to be a challenge for the TG. The desired higher resolution data was not available freely and existing contracts between national MODs and meteorological offices did not include the delivery of such data for research projects. Where weather data is required for future simulation exercises, this requirement needs to be included in existing national contracts, or preferably for NATO to provide access to such data for all participants.

It is recommended that the outputs from MSG-156 are taken forward into a new SISO Study Group (SG) to assess and determine how the DSE specific aspects can be addressed. This should include a review of the existing SISO 'Reuse and Interoperation of Environmental Data and Processes (RIEDP)' Product Development Group (PDG) activities and 'Cloud Based M&S' (CBMS), since these might already cover some of the standards required. Outputs from MSG-156 should also be used to inform activities carried out as part of the NATO MSG-193 Specialist Team on "Modelling and Simulation Standards in Federated Mission Networking (FMN)".

Finally, it is proposed that NATO and/or member nations should consider providing and hosting the key services that are needed for a DSE. The provision of a Terrain Service, Weather Service and various modification services would significantly reduce the burden of setting up future distributed simulation exercises supported by a DSE.

Environnements synthétiques dynamiques corrélés, destinés à la simulation répartie

(STO-TR-MSG-156)

Synthèse

La modélisation et simulation (M&S) est une capacité importante pour l'alliance de l'OTAN et ses pays partenaires en matière d'entraînement interarmées, collectif et de coalition de défense, de développement des capacités, de planification et préparation des missions et d'aide à la décision. Les environnements opérationnels de défense sont extrêmement dynamiques, puisque l'état de l'environnement physique influence le comportement des forces (par exemple, effets des conditions météorologiques sur la mobilité des véhicules terrestres) et que les effets du comportement physique (cinétique) des forces influencent l'état de l'environnement (par exemple, endommagement de bâtiments, infrastructures, etc., par les munitions). Les pratiques, normes et technologies actuelles de M&S produisent principalement des représentations statiques de l'environnement extérieur dans les simulations réparties, sur la base d'ensembles de données environnementales communes et en réutilisant des bases de données environnementales. Lorsque des éléments dynamiques sont représentés dans les systèmes de simulation actuels, ils sont fréquemment mis en œuvre d'une manière scénarisée et propre à un système donné. Cela limite la capacité et le champ d'interopérabilité des systèmes hétérogènes de simulation répartie et a des conséquences sur l'utilisation de la M&S dans les applications telles que l'entraînement des coalitions, qui requiert des représentations communes et cohérentes d'environnements opérationnels pour garantir des conditions de combat assez bonnes.

Le MSG-156 a été lancé en 2017 sous la forme d'un groupe de travail (TG) triennal chargé de combler l'écart existant entre les capacités techniques existantes et le besoin de représenter les défis des environnements réels dans les systèmes de M&S. Son objectif était d'étudier comment un environnement synthétique dynamique (DSE) corrélé pourrait être représenté dans de futures simulations réparties. Le groupe de travail se composait d'experts issus des gouvernements, des instituts de recherche et du monde industriel de tous les pays partenaires de l'OTAN et incluait à la fois des développeurs (fournisseurs) et des consommateurs (utilisateurs) d'environnements synthétiques et de simulation.

Les activités de recherche menées par le TG MSG-156 éclaireront l'un des objectifs clés du plan directeur de l'OTAN en matière de M&S, autrement dit, « développer une architecture d'interopérabilité standard de l'OTAN pour les applications de simulation et les éléments à l'appui ».[2]

Après avoir étudié les capacités existant pour les environnements dynamiques dans les systèmes de simulation et avoir enquêté sur la technologie de pointe et les algorithmes des simulations et jeux de divertissement, le groupe de travail a élaboré des schémas de modélisation conceptuelle sur la base de cas d'utilisation, afin d'identifier les interactions clés nécessaires dans un DSE. Les concepts de modélisation et simulation en tant que service (MSaaS) ont formé la base d'une architecture de solution conceptuelle pour le DSE. Le groupe de travail a étudié les spécificités du terrain dynamique et des conditions météorologiques réalistes pour affiner la démarche conceptuelle et parvenir à une architecture détaillée de solution permettant la représentation cohérente d'un environnement synthétique dynamique au sein de systèmes hétérogènes de simulation répartie.

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[2] NATO Modelling and Simulation Master Plan, Version 2.0, 14 September 2012, Document AC/323/NMSG(2012)-015.

Le concept fondamental de cette architecture de solution est que les services communs sont chargés de gérer et diffuser les données d'environnement au sein de l'exercice de simulation. Cela signifie que les fédérés de la M&S utilisent un service de terrain pour obtenir des informations sur le terrain et un service météorologique pour obtenir des informations sur les conditions météorologiques. L'existence d'un seul service responsable de la gestion de ces données peut atténuer beaucoup de problèmes de corrélation. De plus, un service spécialisé particulier est chargé d'apporter les modifications dynamiques à la représentation synthétique de l'environnement opérationnel, ce qui supprime les problèmes de corrélation susceptibles de se produire lors de la mise en œuvre locale de ces modifications dans chaque système. Ces services de modification des données communiquent leurs changements au service de terrain, permettant ainsi à tous les fédérés d'accéder aux données mises à jour depuis le service de terrain.

Après la mise au point de l'architecture conceptuelle de DSE, le MSG-156 a réalisé une démonstration servant de validation de principe, pendant laquelle des simulations et services fédérés fournis par les pays participants à l'aide d'outils et de produits de différents partenaires industriels ont été déployés, intégrés et exécutés selon cette architecture. Bien que le nombre de simulations et services fédérés disponibles ait été limité, la démonstration a prouvé que l'architecture de solution était réalisable et qu'elle contribuerait à la réalisation de modifications dynamiques et à leur représentation cohérente dans des simulations réparties. La démonstration du concept a également permis de déterminer quels aspects de l'architecture nécessiteraient d'autres recherches avant d'atteindre un niveau de maturité technologique (TRL) convenant au soutien d'exercices de simulation opérationnelle.

En raison des limites de temps et d'échelle, la technologie employée dans l'architecture de DSE basée sur la MSaaS n'est pas encore suffisamment évoluée pour être mise en œuvre dans les systèmes de simulation opérationnelle. Le groupe de travail recommande donc de mener une expérience à plus grande échelle, afin d'évaluer comment l'architecture de solution se comporte dans un environnement où les services sont soumis à un cas d'essai plus réaliste et plus contraignant.

L'architecture de DSE dépend de la présence d'interfaces normalisées dans les différents services. Bien que certaines d'entre elles soient déjà matures, par exemple les interfaces OGC diffusant des informations géographiques, il faudra envisager de développer d'autres interfaces qui pourront servir de futures normes ouvertes. En outre, il convient d'étudier comment un nouveau format de partage de contenu tridimensionnel pourrait prendre en charge la distribution et la diffusion en direct de contenu du modèle tridimensionnel auprès de systèmes de simulation ou apporter des modifications dynamiques au contenu du modèle tridimensionnel pendant l'exécution de simulations.

L'acquisition de données météorologiques du monde réel s'est révélée être une gageure pour le groupe de travail. Les données à haute résolution souhaitées n'étaient pas disponibles gratuitement et les contrats existants entre les ministères nationaux de la Défense et les agences météorologiques n'incluaient pas la fourniture de ces données à des fins de recherche. Lorsque des données météorologiques sont nécessaires à de futurs exercices de simulation, cette exigence doit être incluse dans les contrats nationaux existants, sinon, et de préférence, l'OTAN doit assurer l'accès à ces données pour tous les participants.

Il est recommandé que les résultats du MSG-156 soient transmis à un nouveau groupe d'étude (SG) de la SISO, qui évaluera et déterminera comment traiter les aspects propres au DSE. Cela devrait inclure un examen des activités du groupe de développement de produits (PDG) « Réutilisation et interfonctionnement des données et processus environnementaux (RIEDP) » de la SISO et de la « M&S dans le cloud » (CBMS), étant donné que ces activités pourraient déjà aborder quelques-unes des normes requises. Les résultats du MSG-156 devraient également servir à renseigner les activités menées par l'équipe spécialisée du MSG-193 de l'OTAN sur les « Normes de modélisation et simulation du réseau de mission fédéré (FMN) ».

Enfin, l'OTAN et/ou les pays membres devraient envisager de fournir et d'héberger les services clés nécessaires à un DSE. La fourniture d'un service de terrain, d'un service météorologique et de divers services de modification réduirait sensiblement le fardeau que représente l'organisation de futurs exercices de simulation répartie pris en charge par un DSE.

Chapter 1 – INTRODUCTION

The use of Modelling and Simulation (M&S) within NATO and across NATO nations is an increasing requirement in support of defence training, capability development, mission rehearsal and decision support in acquisition processes [1]. Consequently, M&S is an important capability for the alliance and its nations. However, current M&S systems have a limited representation of military operational environments which are highly dynamic, where the state of the physical environment impacts force behavior (e.g., effects of weather on ground vehicle mobility), and the effects of military physical (kinetic) force behavior impacts the state of the environment (e.g., munition damage to buildings, infrastructure, etc.). Where dynamic elements are currently implemented in simulation systems, they are often carried out in a bespoke and pre-scripted manner, which limits the capability and scope for simulation interoperability.

Figure 1-1: Dynamic Aspects of the Environment Encountered during Missions.

In 2016 a NATO MSG Exploratory Team ET-045 "Dynamic Synthetic Natural Environments for Distributed Simulation" was initiated to investigate whether the topic of a correlated dynamic synthetic environment in distributed simulation required further research. This identified the main challenges for achieving correlated dynamic terrain [2]. The conclusion was that many open issues related to correlated Dynamic Synthetic Environments (DSE) are present and that these issues will limit the usability of distributed simulation for NATO in the future. Most of these problems are of a technical nature, including the fact that there are no open standards or proven methods to enable the integration of weather, weather effects and physical (kinetic) warfare effects on the environment in a coherent and consistent manner across distributed M&S systems. In response to the findings from ET-045, a Technical Activity Proposal (TAP) for a 3-year Task Group (TG) was submitted to the NATO MSG Business Meeting in Spring 2017 and this became MSG-156, which started in September 2017.

1.1 DEFINITIONS

This report contains a couple of frequently used terms defined by ET-045, i.e.:

- A **Synthetic Environment (SE)** is a collection of elements that represent the physical world within which (simulation) models of systems exist and interact (i.e., terrain, weather, oceans, space). It includes both data and models representing the elements of the environment, their effects on systems, and models of the impact of systems on environmental variables.

- A **Dynamic Synthetic Environment (DSE)** is a SE for which the elements can be changed or deformed during the simulation, such as the impact of rain on the terrain surface. This can be due to interactions within the environment (e.g., weather affecting terrain conditions), due to interactions from simulation entities (e.g., weapon effects or digging by units) or due to external interactions (e.g., instructor driven changes).

Instead of using the definition SE, it is also common to refer to the Synthetic Natural Environment (SNE). However, ET-045 and MSG-156 do not consider that the term SNE covers all environment aspects in a SE, as there are also non-natural elements that need to be represented. The MSG-156 TG therefore decided on adopting the use of SE in this report. Subsequent to this, the TG has become aware that in the next AMSP-01 edition [3], the term SNE will be replaced by Synthetic Physical Environment (SPE), which better captures the scope. Since MSG-156 had already written several publications and most of the report using the term SE, it was decided to remain with SE for the purpose of this report.

1.2 OBJECTIVES

The objectives of the MSG-156 Task Group (TG) were defined as:

1) To define best practices, required methodologies, technologies and inform requirements for standards needed to achieve a correlated dynamic SE in future distributed simulation exercises; and
2) To evaluate methodologies and technologies through concept experimentation.

1.3 PROGRAM OF WORK

To achieve the objectives identified above, MSG-156 defined a Program of Work that includes the following activities (see Figure 1-2):

a. **Identity requirements for a DSE:** Identify the functional requirements for a DSE in a distributed simulation, including which aspects of real-world operations are critical to represent in the simulation; this is discussed in Chapter 2.

b. **Survey existing solutions:** Obtain an understanding of the current state of the art technology for DSEs, in order to identify gaps that need to be addressed to achieve a correlated DSE; this is discussed further in Chapter 2.

c. **Define Use Cases:** Identify relevant operational scenarios as a basis for evaluating methods and technologies to support a DSE architecture; these Use Cases are discussed further in Chapter 3.

d. **Define solution concepts:** Define concepts of solutions to achieve a correlated DSE in a distributed simulation. Chapter 3 presents selected Use Cases and conceptual diagrams of several relevant dynamic effects, such as trafficability, which the group used as a basis for developing the conceptual architecture of the solution concept. Chapter 4 and 5 go into more detail on the two main topics addressed by the group, i.e., dynamic terrain and dynamic weather, covering relevant dynamic effects, data sources and existing standards. Chapter 6 combines all these findings in the solution architecture for DSEs that MSG-156 proposed.

e. **Concept demonstration:** Make a (partial) implementation of the solution concept, so that its feasibility can be demonstrated, and practical lessons can be learned, and whether the solution concept works and fulfils the identified requirements and which areas need further research. The concept demonstration is discussed in more detail in Chapter 7.

f. **Write technical report:** The final activity is to write this report and combine all the lessons learned into recommendations for the M&S community towards achieving correlated DSE; this includes the identification of suitable technologies and methods, and advice on standards that should be developed.

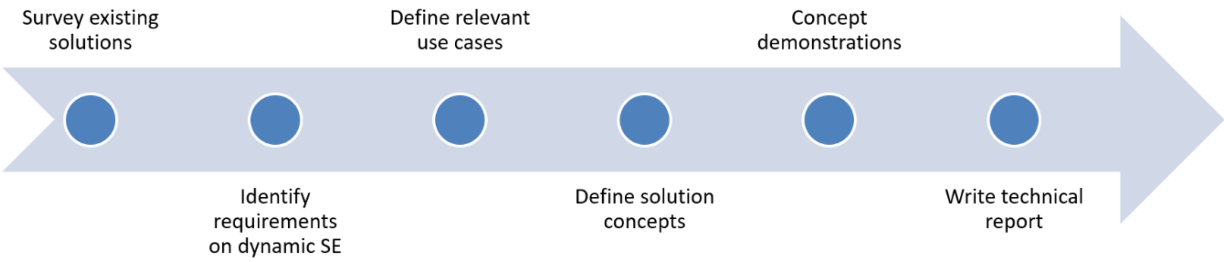

Figure 1-2: MSG-156 Program of Work.

1.4 REFERENCES

[1] NATO Modelling and Simulation Master Plan, Version 2.0, 14 September 2012, Document AC/323/NMSG(2012)-015.

[2] Exploratory Team MSG-ET-045 Dynamic Synthetic Natural Environments for Distributed Simulation, Final Report, September 2017.

[3] NATO Modelling and Simulation Standards Profile. AMSP-01, Edition (D), Version 1. September 2017.

Chapter 2 – MOTIVATION FOR A DSE

Military operations are performed in a world where the environment is dynamic and where weather and warfare effects have an impact on operational capability, including platform and systems behavior. Examples include:

- The effects of precipitation such as rain or snow on the terrain surface which can affect ground vehicle mobility:
- The effects of cloud formations and rain on airborne sensors;
- The effects of wind on air platforms, e.g., Unmanned Air Vehicles (UAVs); and
- The effects of munitions damage to the terrain surface (e.g., craters) and road infrastructures, which impact route planning.

When training or experimenting using distributed simulation these dynamic aspects of the environment need to be supported in a common and consistent way to provide a coherent representation of the synthetic environment across dissimilar simulation systems. Without this, fair-fight issues will occur between the different participants of the exercise and the usage value is reduced. For example, if one system restricts the navigation of an entity due to a blocking crater in the terrain while the other does not, this results in unfair conditions and, as a consequence, reduced training or experimentation value of the exercise.

This chapter elaborates on the current state of the art in Dynamic Synthetic Environments (DSEs), examining both existing simulation systems and available technology. Inspired by this, a list of the main requirements for DSEs that were identified by the TG is presented.

2.1 SYSTEM AND TECHNOLOGY SURVEY

As part of the PoW, MSG-156 started out with surveying the state of the art, both in currently fielded simulation systems and in available algorithms and technology.

2.1.1 Current Capabilities of Simulation Systems

The TG performed a survey of 17 selected simulation systems currently in active use in the participating nations. These included fixed-wing and rotary wing flight simulators, FAC/FO training systems, tactical simulators for ground vehicles and infantry, and CGF systems. The survey was performed using a questionnaire, see Appendix A, of which the main points to capture were:

- What are common capabilities with respect to dynamic SEs in simulation systems?
- Which interesting unique capabilities can be found in current systems?
- Is interoperability of dynamic SEs (to some extent) supported in current systems?

A brief summary of the findings is detailed below. Note that these findings were obtained using only a small sample (17) of military simulation systems currently employed within NATO and the survey was performed back in 2018. The capabilities and dynamic effects found in the surveyed system are (C = common functionality found in multiple systems, U = specialized functionality):

- Weather effects:
  - [C] Time-of-day based sun/moon/star light;
  - [C] Configurable cloud layers;

  - [C] Visualization of precipitation (rain, hail, snow);
  - [C] Thermal simulation takes heating up due to sun into account;
  - [U] Weather state can have a degrading effect on instrumentation and sensors; and
  - [U] Weather can vary per location within the SE (including transitions in-between).
- Natural effects on environment:
  - [C] Trafficability takes soil types into account (**Note**: soil conditions are static);
  - [C] Dust and brown-out based on soil types (**Note**: soil conditions are static);
  - [C] Scenario starts with a snow layer (**Note**: soil conditions are static);
  - [U] Precipitation has a deteriorating effect on trafficability; and
  - [U] Snow accumulates into a snow layer.
- Human geophysical effects on environment:
  - [C] Combat engineering as part of the scenario definition (i.e., by the instructor); and
  - [U] Specialized vehicles can lay a bridge to pass a water obstacle.
- Force engagement effects on environment:
  - [C] Buildings with fixed, pre-computed damage states;
  - [C] Craters as simple models on top of terrain skin;
  - [C] Trees and utility poles falling over;
  - [U] Craters that deform the terrain mesh; and
  - [U] Dynamic (physics-based) damage to buildings.
- Interoperability:
  - [C] Distributing entity state and events using DIS, HLA;
  - [C] Controlling the visual through CIGI;
  - [C] Web data serving standards supported (e.g., WMS/WFS);
  - [U] SEDRIS support;
  - [U] Distributing dynamic SE within a network running the same simulation system (i.e., multi-user);
  - [U] Service-based approaches (terrain service, weather service); and
  - [U] Custom HLA FOM for dynamic SE updates.

The conclusions of the survey are:

- Correlation of dynamic environment changes is either not supported or limited to multi-user networks running the same simulation system; however, there are some promising server-based approaches that use a single centralized data repository to improve correlation;
- Each simulation system contains a subset of dynamic SE capabilities, which are mainly pre-scripted;
- Combat engineering and trafficability with dynamic soil conditions somewhat underdeveloped;
- Technical implementations, constraints and realism of dynamic effects differ quite a lot (performance, scalability, physics-based vs. model-switching).

2.1.2 State of the Art Algorithms and Technology

Ongoing advances in hardware performance and gaming technology, such as physics and rendering engines, continue to improve the performance and scalability of real-time, complex algorithms for computing dynamic effects. Especially in the entertainment gaming domain, many examples of real-time physics-based implementations of dynamic effects can be found. A good example of this is physics-based destruction of buildings (as featured in for instance the Battlefield game series), where walls and roofs are fractured according to the force, point and direction of impact. Many recent games also feature a dynamic weather system, sometimes including snow accumulation. Finally, there are examples of games that combine a high-end physics model of vehicle dynamics with terrain deformation and dynamic soil conditions (probably the best example of this is the Spintires series of games).

A recent survey was also carried out by Smelik et al. [1]. As concluded in the survey as well, the technology, algorithms and hardware performance are at sufficient level to support fully dynamic synthetic environments, however, interoperability and correlation across heterogeneous systems remain open issues hindering the transition. Since correlation across heterogeneous systems is typically not relevant for the entertainment gaming industry, the solution to this will have to be provided by the M&S community, while still taking advantage of the available game technology.

2.2 REQUIREMENTS FOR A DSE

The MSG-156 TG recognized a capability gap in current defence simulation and Synthetic Environments (SEs). This was identified as a lack of consistent representation of dynamic environments across simulation systems, specifically the representation of meteorological data and physical warfare effects, and associated 2nd and 3rd order effects on the operational environment. Based on how the dynamic environment affects real world operations and how such operations would be simulated in a distributed simulation environment, MSG-156 has defined a number of high-level requirements, listed in Table 2-1, Table 2-2, and Table 2-3.

Table 2-1: Overall Requirements Dynamic Synthetic Environment Architecture.

REQ_DSE_1	It should be possible to dynamically change the environment at runtime during the simulation exercise.
REQ_DSE_2	It should be possible to have the dynamic environment changes triggered by: • Processes within the environment itself, e.g., weather affecting terrain conditions. • Events caused by participants of the exercise, e.g., the detonation of a weapon. • The instructor or white cell operator of the simulation exercise
REQ_DSE_3	The DSE architecture should support the inclusion of derived effects from the dynamic changes as well, e.g., destruction of a bridge is not only visual, but also affects the navigation of constructive entities.
REQ_DSE_4	The DSE shall be sufficiently correlated, so that different participants in the distributed simulation make the same assessment of the situation within the mission.
REQ_DSE_5	The DSE architecture should be vendor neutral.
REQ_DSE_6	The DSE architecture should use open standards, in accordance with the NATO M&S Standards Profile (NMSSP) where appropriate [2].
REQ_DSE_7	The DSE architecture should support terrain and weather data for land and air operations. Data for underwater operations, sea states, space weather or other planets is out of scope for the TG. The DSE architecture should be flexible enough though, so that additional data layers can be added to the concept later.

Table 2-2: Requirements for Dynamic Terrain.

REQ_DT_1	The dynamic terrain should be represented consistently to the different participants in the simulation exercise, e.g., the presence of craters or the damage to objects.
REQ_DT_2	The dynamic terrain should have a consistent effect on entities and their systems in the simulation exercise, e.g., on their trafficability or line of sight.
REQ_DT_3	The damage to objects should be consistent with the characteristics of the weapon that caused the damage.

Table 2-3: Requirements for Dynamic Weather.

REQ_DW_1	The weather should change with time and space during the simulation exercise.
REQ_DW_2	The weather should be represented consistently to the different participants in the simulation exercise.
REQ_DW_3	The DSE architecture should support representing weather effects on entities and their systems consistently in the simulation exercise, e.g., trafficability of ground vehicles or on the performance of sensors.
REQ_DW_4	The representation of weather in simulation systems should support either historical or live weather data from authoritative data providers.

2.3 REFERENCES

[1] Smelik, R.M., Wermeskerken, F.P.J. van, Krijnen, R. and Kuijper, F. (2018), Dynamic Synthetic Environments: A Survey. Journal of Defense Modeling and Simulation: Application, Methodology, Technology, November 2018 https://journals.sagepub.com/doi/10.1177/1548512918811954.

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Chapter 3 – TECHNICAL APPROACH

This chapter discusses the technical approach that was followed by MSG-156 (previously presented in Refs. [1], [2]). As discussed in the section about the Program of Work, the initial steps of the technical approach focused on:

1) Defining relevant use cases that illustrate where dynamic environments are relevant in operational missions;
2) Performing conceptual modelling of the interactions that are relevant for dynamic environments; and
3) Defining a conceptual solution architecture.

These three topics will be described in more detail in this chapter.

3.1 USE CASES

To make the discussions about dynamic environments more concrete, MSG-156 defined four use cases that illustrate the importance of dynamic environments in an operational context. Each of these use cases focuses on a specific aspect of a dynamic environment, this allows the use cases to remain relatively small and therefore it is easier to work with them when working out the technical details of the interactions. The following four use cases have been defined:

1) Close Air Support (CAS).
2) Air engagement in realistic weather.
3) Trafficability influenced by weather.
4) Terrain modifications.

Each of them will be described in more detail in the coming sections, describing the operational situation depicted by the use case and the dynamic environment interactions that are involved in them. In further activities, like defining the conceptual model or the concept demonstration, reference is made to (parts) of these use cases.

3.1.1 Use Case #1: Close Air Support (CAS)

During a CAS mission the Forward Air Controller (FAC) on the ground and the aircrew need to visually identify the same target that should be engaged (Figure 3-1). This is done by describing the target using a standard report and by voice and/or datalink communications. Using the sensors of the aircraft, including a targeting pod, the aircrew will attempt to identify the correct target. Once the target has been correctly identified the aircrew will start the weapon delivery and afterwards the weapon damage will be assessed by both the FAC and the air crew to determine whether the target was destroyed.

When this Use Case is performed using distributed simulation systems, it is important that the operators can effectively identify and communicate about the target object and assess the damage to the object.

Dynamic environment requirements in this use case: REQ_DT_1, REQ_DT_3.

Figure 3-1: A Forward Air Controller Team (Source Defensie.nl).

3.1.2 Use Case #2: Air Engagement in Realistic Weather

An Unmanned Air System (UAS) is deployed to conduct Intelligence, Surveillance and Reconnaissance (ISR) activities and identify a ground target (Figure 3-2). The UAS is configured with weapons, on-board radar, and an Electro-Optic (EO) sensor. As the UAS carries out its reconnaissance of the operational area a weather front passes through bringing increasing cloud cover and some precipitation. An enemy manned aircraft is tasked with destroying the UAS. During the air-to-air engagement sensors on the airborne platforms are tracking each other. The clouds sometimes block the visual line of sight between the two airborne platforms and precipitation in the atmosphere introduces disturbances and degradation on the sensors. An air-to-air missile is subsequently fired at the UAS. The seeker of this missile will track the UAS and guide the missile to the target.

Figure 3-2: An Unmanned Air System (UAS).

When this Use Case is performed using distributed simulation systems, it is important the effects of the weather on the various systems and sensors are applied in a consistent way, else fair-fight issues could be introduced.

Dynamic environment requirements in this use case: REQ_DW_1, REQ_DW_2, REQ_DW_3.

3.1.3 Use Case #3: Trafficability Influenced by Weather

A convoy of armored vehicles and supply trucks is traversing a difficult mountainous and densely vegetated terrain on a multi-day trip to resupply an isolated Forward Operating Base (Figure 3-3). Not all local roads are paved and in good condition, and heavy rainfall causes some of the dirt roads to become slippery, forcing the convoy to advance at reduced speed. The rain changes to snow, and with the decreased visibility and the trucks getting stuck in the high snow volumes, the convoy commander no longer considers it safe to continue and decides to take a long detour using only paved well-maintained roads.

Figure 3-3: Terrain Conditions Affecting Trafficability (Source Defensie.nl).

When this Use Case is performed using distributed simulation systems it is important that the effect of the dynamic terrain conditions on the trafficability of the different systems is implemented in a consistent way. Besides that, the representation of the weather and the terrain state should be consistent, so that operators have the same perception of it.

Dynamic environment requirements in this use case: REQ_DT_2, REQ_DW_1, REQ_DW_2, REQ_DW_3.

3.1.4 Use Case #4: Terrain Modifications

A combat engineering unit prepares a defensive position for infantry in open terrain by digging a network of trenches. Later on, opposing forces applies a barrage of artillery fire on the reinforced positions, resulting in numerous large craters in the terrain and damage to the trenches (Figure 3-4). Opposing infantry units and vehicles now use these crates to advance on the defensive position under cover.

Figure 3-4: Example of Crater in the Terrain (Source Defensie.nl).

3.2 CONCEPTUAL MODELS

To get a better understanding of the various concepts that are involved in a dynamic SE and to understand how these concepts are related, the MSG-156 Task Group created conceptual model diagrams. The idea behind these conceptual model diagrams is to identify which aspects are relevant to be included in the simulation and how they influence each other.

The four use cases described in the previous section were used as basis for the conceptual model diagrams, but since the conceptual model diagrams focus on the interactions with the environment they have been organized slightly differently. The following four conceptual model diagrams have been created:

- The influence of terrain and weather on the trafficability of vehicles.
- Terrain and object deformation due to weapon effects.
- Flight dynamics of aerial vehicles influenced by weather.
- Sensor performance affected by weather.

The approach the MSG-156 TG used for creating the conceptual model diagrams was to look at the concepts that are involved in the different interactions and to depict graphically using arrows how they are related to each other. CMap [3] was used to capture this information in diagrams. In the sections below each of the four diagrams is discussed in more detail.

The conceptual model diagrams show the concepts and interactions that are involved. This means these concepts need to be implemented in the distributed simulation environment to be able to simulate a dynamic SE in a realistic way. Therefore, the information from these diagrams helped the Task Group in defining the conceptual solution architecture. The various aspects that have been identified in the conceptual model diagrams have to become the responsibility of a specific model or component within the simulation environment, e.g., it has to be decided who is responsible to update terrain conditions as a result of the weather. By checking which concepts are related it also becomes possible to identify the interfaces that are needed to communicate the required inputs or outputs between the various simulation components, e.g., the model that calculates the trafficability needs to receive information about the terrain surface condition and the resulting maximum speed has to be provided to the ground vehicle dynamics model.

The conceptual model diagrams are therefore a tool that helps to define the responsibilities of the various simulation models in a logical way, since the diagrams help to understand the real-world interactions that are being represented. Once these model responsibilities have been identified, the interfaces needed to exchange information can also be defined in a logical way.

3.2.1 CM Diagram 1: The Influence of Terrain and Weather on the Trafficability of Vehicles

The first conceptual model diagram, see Figure 3-5, focuses on how terrain and weather influence the trafficability of vehicles.

The central concept in this diagram is ‘trafficability’, which limits the speed at which a vehicle travels. The trafficability is influenced by the slope of the terrain, the surface conditions of the terrain and the characteristics of the vehicle (e.g., weight of the vehicle, whether the vehicle has tracks or wheels). The speed of the vehicle is also influenced by the behavior of the driver. Both of these aspects can be influenced by the weather. For example, the surface conditions can be modified by the weather, e.g., precipitation making the ground more moisture and resulting in muddy roads. The weather can also affect the behavior of the driver, e.g., fog restricting the visibility, as a result of which the driver does not dare to risk driving any faster.

This conceptual model diagram shows that dynamic changes to the environment can influence the trafficability in different ways:

- Changes in the slope of the terrain affect trafficability, e.g., the addition of a crater affects how a vehicle can move;
- Changes in the terrain surface and its conditions affect trafficability; these changes can be due to weather effects or due to force engagement effects; and
- Changes in the weather do affect the trafficability directly, as they affect the driver behavior, and indirectly as they can influence the surface conditions.

3.2.2 CM Diagram 2: Terrain and Object Deformation Due to Weapon Effects

The second conceptual model diagram, see Figure 3-6, focuses on how terrain and objects can be deformed due to weapon effects.

The central concept in this diagram is the detonation that is caused by the weapon, this can be either an Improvised Explosive Device (IED), mortar or bomb. This detonation can change the elevation profile of the terrain and it can modify features in the terrain as well. Examples of the last are damage to buildings or bridges, but also more abstract changes as modifications of the navigation network. The characteristics of the munition and where the detonation occurs in the terrain affects terrain deformation, i.e., how big the modifications to the terrain surface and features will be.

These modifications to the terrain and its objects can be an input into the trafficability as described in the first conceptual model diagram. They can also be observed visually by operators.

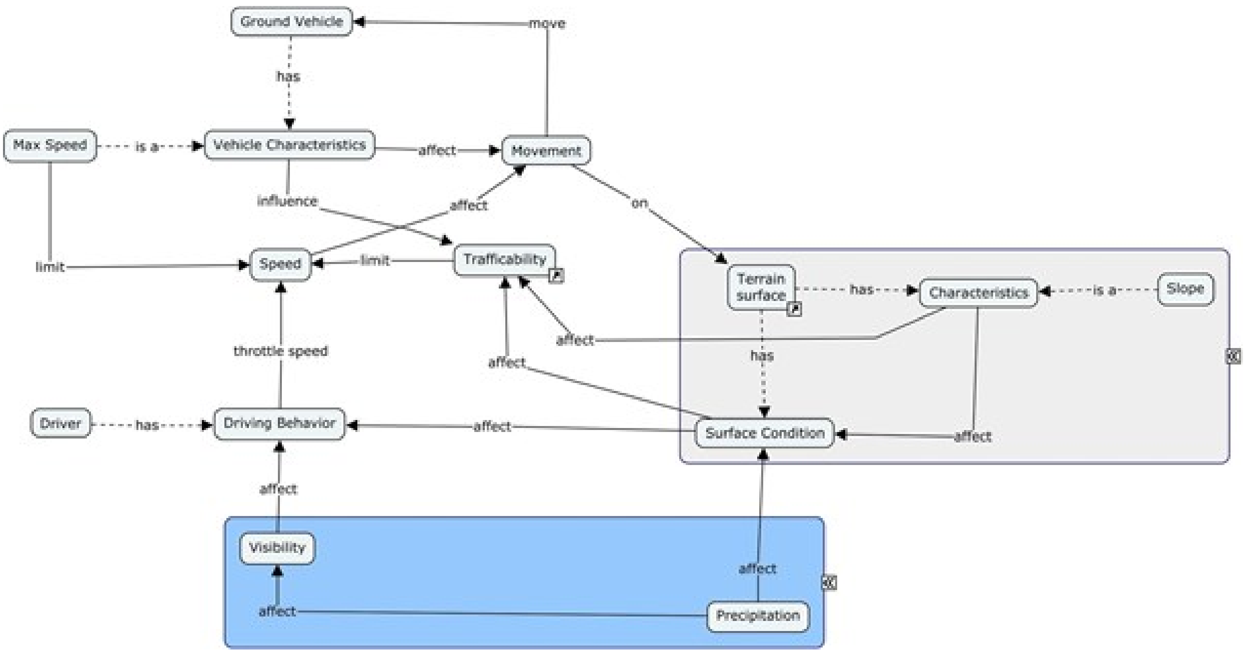

Figure 3-5: Conceptual Model Diagram for the Influence of Terrain and Weather on the Trafficability of Vehicles.

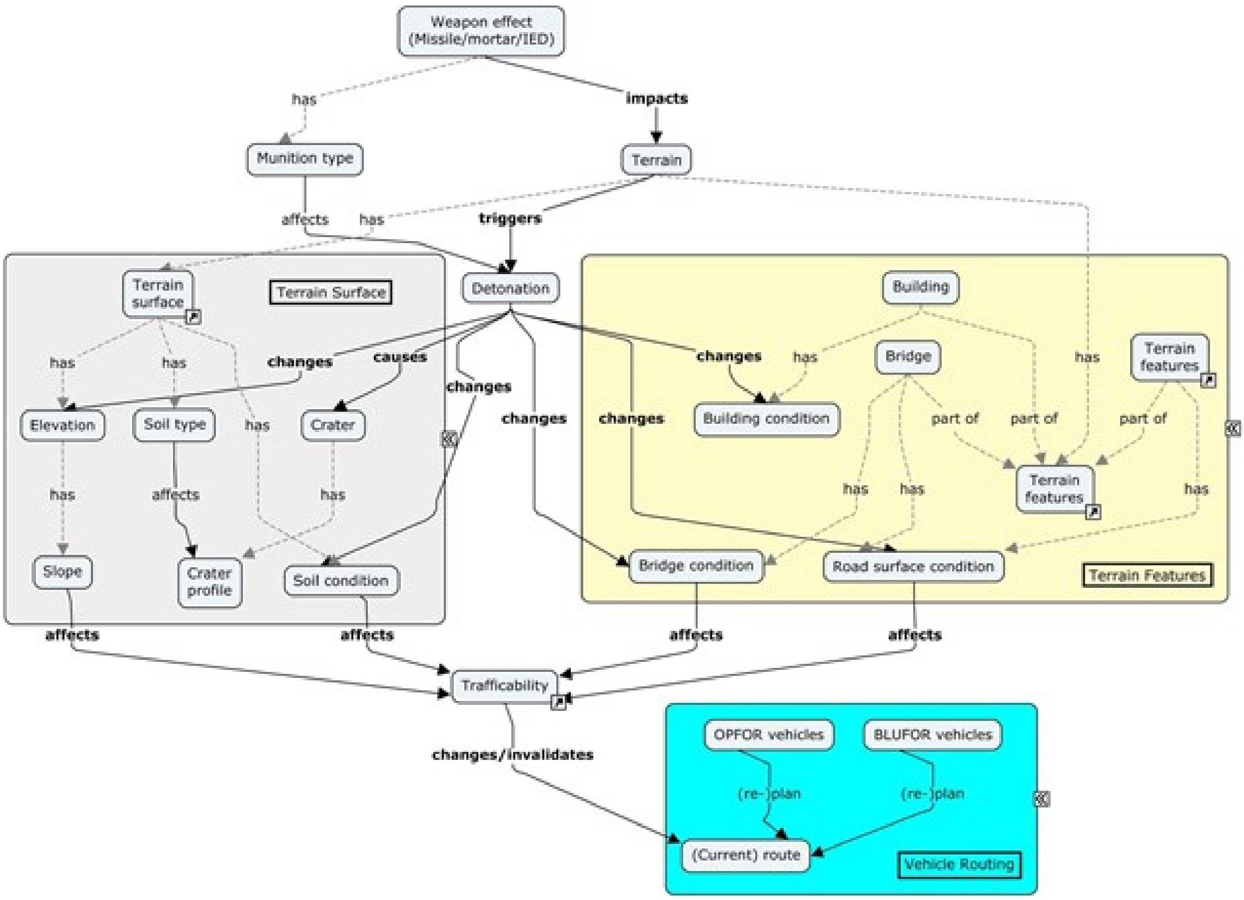

Figure 3-6: Conceptual Model Diagram for Terrain and Object Deformation Due to Weapon Effects.

3.2.3 CM Diagram 3: Flight Dynamics of Aerial Vehicles Influenced by Weather

The third conceptual model diagram, see Figure 3-7, focuses on how the flight dynamics of aerial vehicles are influenced by the weather.

The central concept in this diagram are the atmospheric conditions, which includes the wind, temperature, pressure, and density of the atmosphere at the location of the aerial vehicle. The flight dynamics of the aerial vehicle are directly influenced by these atmospheric conditions. However, there is also an operator that controls the aerial vehicle, this can be either a pilot in the vehicle or an operator of an unmanned aerial vehicle on the ground. These operators can observe the weather using the sensors that they have and based on that influence their control actions, and these control actions also influence the flight dynamics. The concept sensors should be seen widely in this case, it includes the eyes of the pilot, but also a weather radar or an optical camera on the vehicle.

This conceptual model diagram makes clear that dynamic changes to the weather, e.g., the change of the atmospheric conditions with location or time, have a direct and indirect influence of the flight dynamics of aerial vehicles.

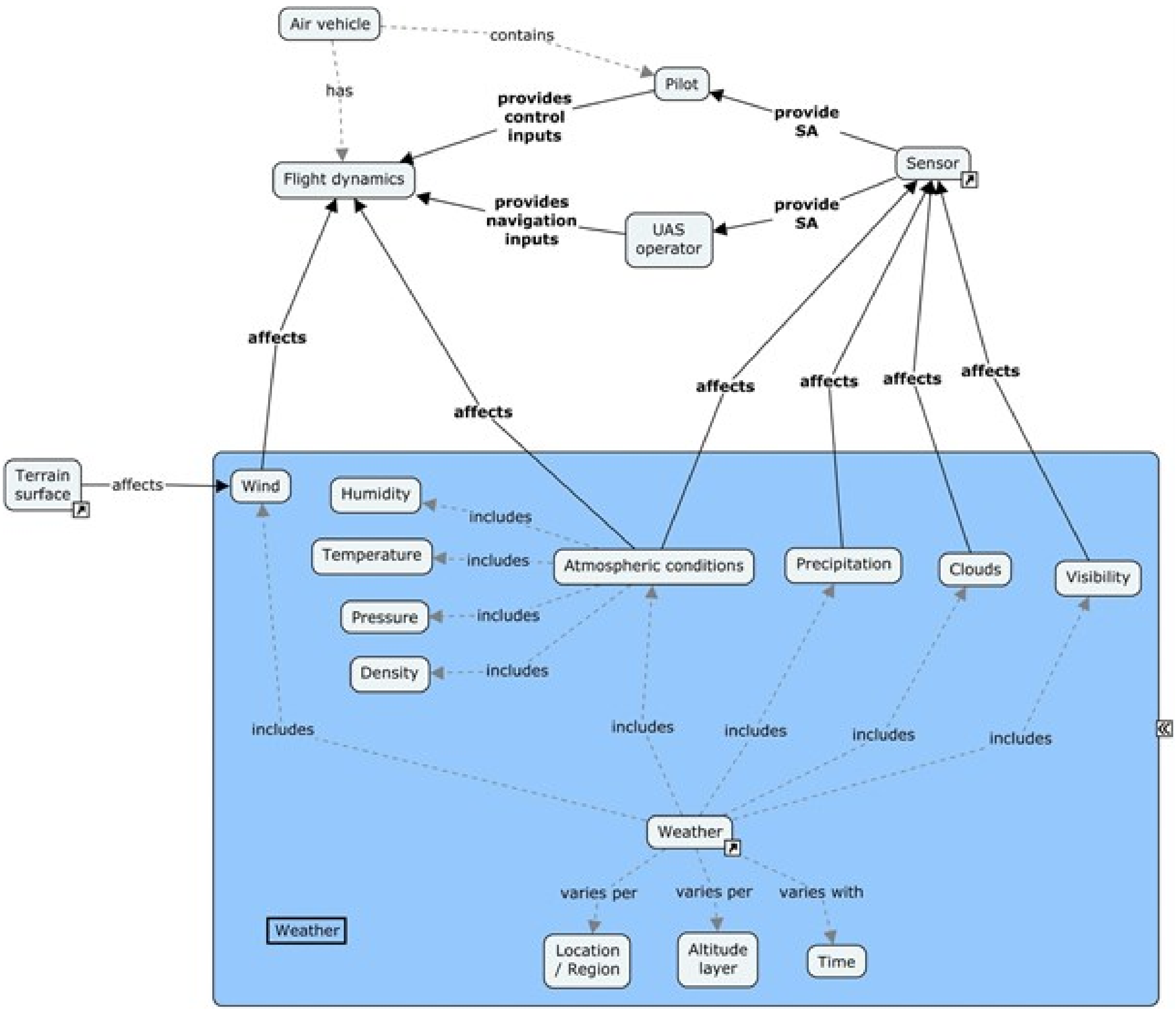

Figure 3-7: Conceptual Modelling Diagram for Flight Dynamics of Aerial Vehicles Influenced by Weather.

3.2.4 CM Diagram 4: Sensor Performance Affected by Weather

The fourth conceptual model diagram, see Figure 3-8, focuses on how weather affects the performance of sensors.

The central concept in this diagram is the radiation that can be observed by the sensor. Depending on the type of sensor it will be a different part of the spectrum that can be observed, e.g., visual, infrared or radar. The transmission of this radiation between the source and the sensor is directly influenced by the atmospheric conditions. For example, clouds will block visual radiation, while radar radiation can travel through it in most cases. The terrain surface, terrain features and the entities do also affect the radiation. Their material characteristics influence how radiation is reflected or created.

This conceptual model diagram makes clear that dynamic changes to the environment affect the sensor performance in two ways. They can change the atmospheric conditions, thereby affecting the transmission of the radiation. Dynamic changes to the environment can also change the geometry or material, which also affects the radiation and thereby the sensor performance.

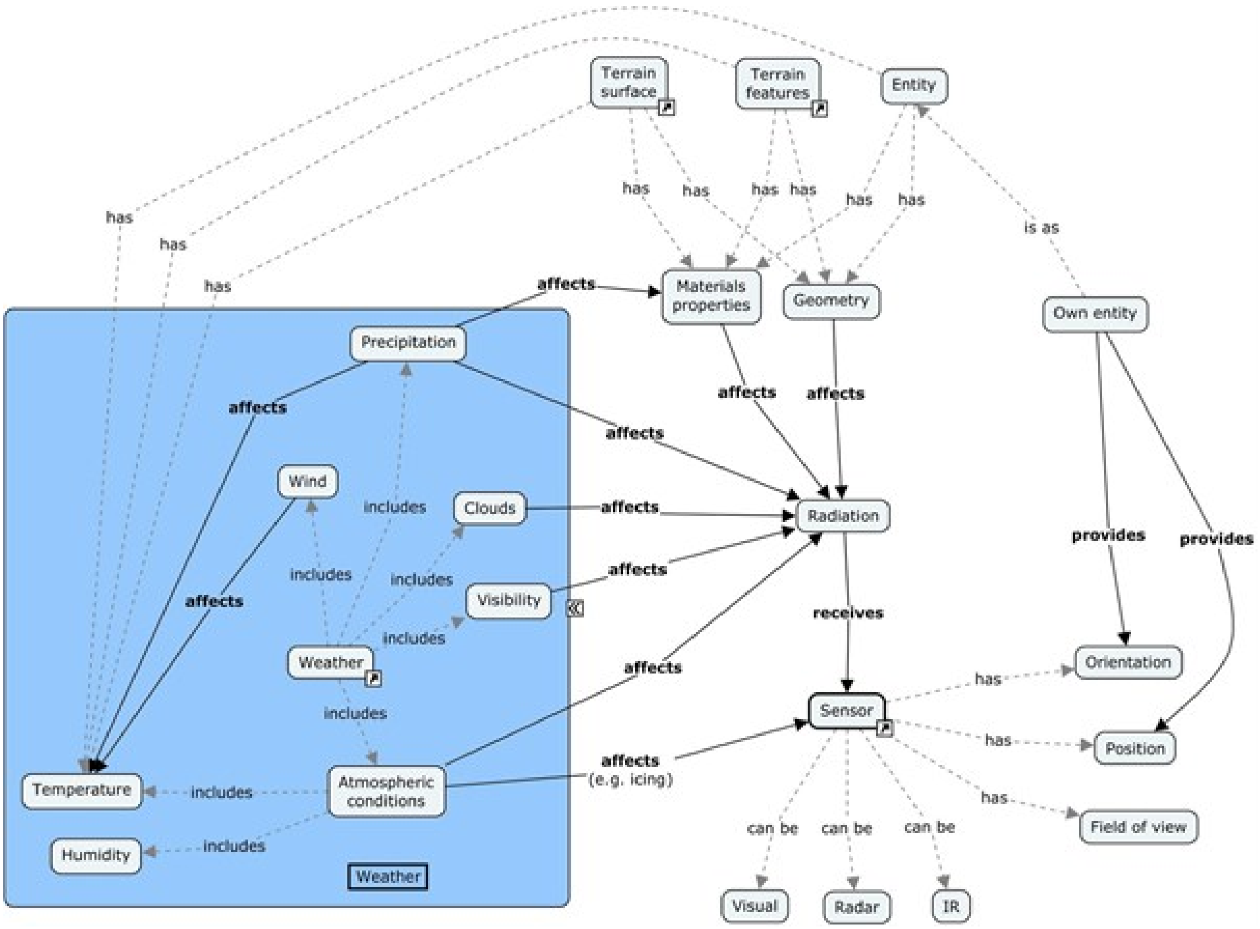

Figure 3-8: Conceptual Modelling Diagram for Sensor Performance Affected by Weather.

3.3 CONCEPTUAL ARCHITECTURE

3.3.1 MSaaS Approach

Based on the concepts and interactions, as identified by the conceptual model diagrams, the MSG-156 TG defined a conceptual architecture to achieve a correlated DSE in a distributed simulation.

One crucial choice the TG had to make is who will be responsible to maintain the state of the DSE. Since the 1990s, the paradigm used in simulation systems has been that each simulation system is responsible to maintain the state of its own SE. This paradigm was mainly chosen with the bandwidth restriction from that period in mind, as making each system responsible for its own SE means only the events that modify the SE must be exchanged between the systems.

Dynamic changes to the SE can be implemented with this paradigm as well. For example, when a detonation event is distributed to indicate that a weapon has detonated, each simulation system can locally determine which crater has been created into the terrain. Based on the weather data each system could also locally calculate the impact this has on the trafficability of vehicles.

However, achieving a correlated static SE proves to be hard already when each system is responsible for its own environment representation. It is still a big challenge to ensure that all simulation systems have a representation of the environment that is sufficiently correlated for the aims of the distributed simulation. Trying to ensure a correlated dynamic SE is achieved with the same approach will be even more challenging. It could for example require that simulation systems use a standardized algorithm to calculate craters. Given all the problems with ensuring a correlated static SE nowadays, the MSG-156 TG has the opinion that it would not be wise to try to achieve a correlated DSE using the same paradigm.

Therefore MSG-156 decided to assign the responsibility to maintain the state of the terrain state or weather state to a single component in the distributed simulation, e.g., a terrain service to maintain the terrain state and a weather service to maintain the weather data. In recent years, an alternative paradigm of Modelling and Simulation as a Service (MSaaS) has been introduced [4] that uses the ‘as a service’ concept with the aim of making simulation more modular. Elements that are needed by different systems in the distributed simulation are provided as services that simulation systems can consume. This improves correlation and makes it easier to achieve fair-fight conditions, as all participants in the exercise can consume the same service. MSG-156 will use the MSaaS concept in its solution architecture. The crucial services here are a terrain service and a weather service that act as a central source for all participants to get their information about the environment.

When talking about dynamic updates to the environment additional services can be added that become responsible to calculate the changes of the environment. For example, one service might be responsible for calculating the craters that are created by detonations, while another service is responsible for determining what the impact of the weather on the conditions of the terrain surface is. These services update the central representation of the environment and all participating systems can retrieve the updated environmental data from there. This makes achieving a correlated dynamic SE much easier. Besides that, each of these services can specialize on specific modifications to the environment and encapsulate the specific knowledge needed for these modifications in one location. The simulation systems that consume the environment no longer need to have knowledge about how the modifications are made. This also means that the simulation systems no longer have a requirement to support local modifications to the environment, which simplifies their implementation and frees computing resources. If the performance of the services is an issue, various instances of the modification service can be used in parallel, where each service is for example responsible for handling a certain region of the operational area.

The MSG-156 TG decided to adopt the MSaaS approach as this was considered to be the most future-proof approach. The Task Group realized that by choosing this direction the results of the work cannot be implemented in simulation systems in the short term (0 – 3 years). The shift from simulation systems that are responsible for their own environment representation to simulation systems that can consume the environment from external services is a big paradigm change. It is important that the interfaces between the various services and the simulation systems are standardized to have a flexible solution where implementations of services from different providers or manufacturers can be swapped based on the needs. The possible benefits of the MSaaS approach are very big however, therefore the MSG-156 TG thinks it is worthwhile to transition in this direction. As will be discussed in the remainder of this final report the TG has made a concept demonstration to demonstrate that a MSaaS approach for a correlated DSE will work.

The TG is also aware of challenges and potential issues with the MSaaS approach. For example, the amount of (terrain) data that needs to be distributed could be a challenge, especially in large scale exercises. Possible solutions for this are deploying multiple instances of the services that provide the data or local caching of the data. Furthermore, many simulation systems apply procedural algorithms to enhance the environment. How to do that in a MSaaS environment and still keep a consistent representation is a challenge that needs to be solved. Part of the procedural content generation might have to be moved to services to ensure correlation. These are just two examples to indicate that the switch to an MSaaS architecture will bring new challenges that need to be solved.

As mentioned above the MSaaS approach involves a paradigm shift in M&S composition, deployment, integration and execution. This means that simulation systems need to be adapted to be able to consume a DSE that is provided via services. The consequence of this is that legacy and existing systems will not be fully capable of working with such a DSE architecture. The TG has accepted this consequence, because of the large potential benefit the MSaaS approach offers in the future. However, it is possible for existing and legacy systems partially co-operate in the DSE MSaaS architecture. Throughout the discussions in this report, design choices are identified that will allow legacy systems to partially work with the DSE representation.

3.3.2 Architecture Components

As explained in the previous section the MSG-156 TG has decided to use a MSaaS based conceptual architecture, where specific services are defined. Figure 3-9 shows this conceptual architecture and its main components:

- A **terrain service** that provides terrain data to all federates in the distributed simulation exercise. The following layers of terrain data are typically provided: imagery, elevation, vector data and 3D models.
- A **weather service** that provides weather data to all federates in the distributed simulation exercise. The weather data includes information such as atmospheric conditions, clouds, precipitation, and sea state.
- Both the terrain and weather service will load and serve data describing the terrain and weather from a **data repository**. Any modifications that are made to the synthetic environment while the simulation is running are stored within the data repository.
- **Query and modification services** that are responsible to either provide a shared interface for specialized queries to be performed (e.g., line of sight, sensor performance), or to modify the terrain data based on events occurring during the simulation. The modified terrain data is stored by the terrain service, so that federates can access the updated terrain data from there again. Examples of modification services are the creation of craters in elevation data based on detonations, modifying the road network based on detonations, or modifying the terrain surface conditions based on the current weather. It is foreseen that there could be many specialized services that focus on the modification of certain terrain layers for specific events.

In the following chapters the details of these services and their interfaces are described in more detail. In the concept demonstration that the MSG-156 TG carried out, an implementation of this architecture was created.

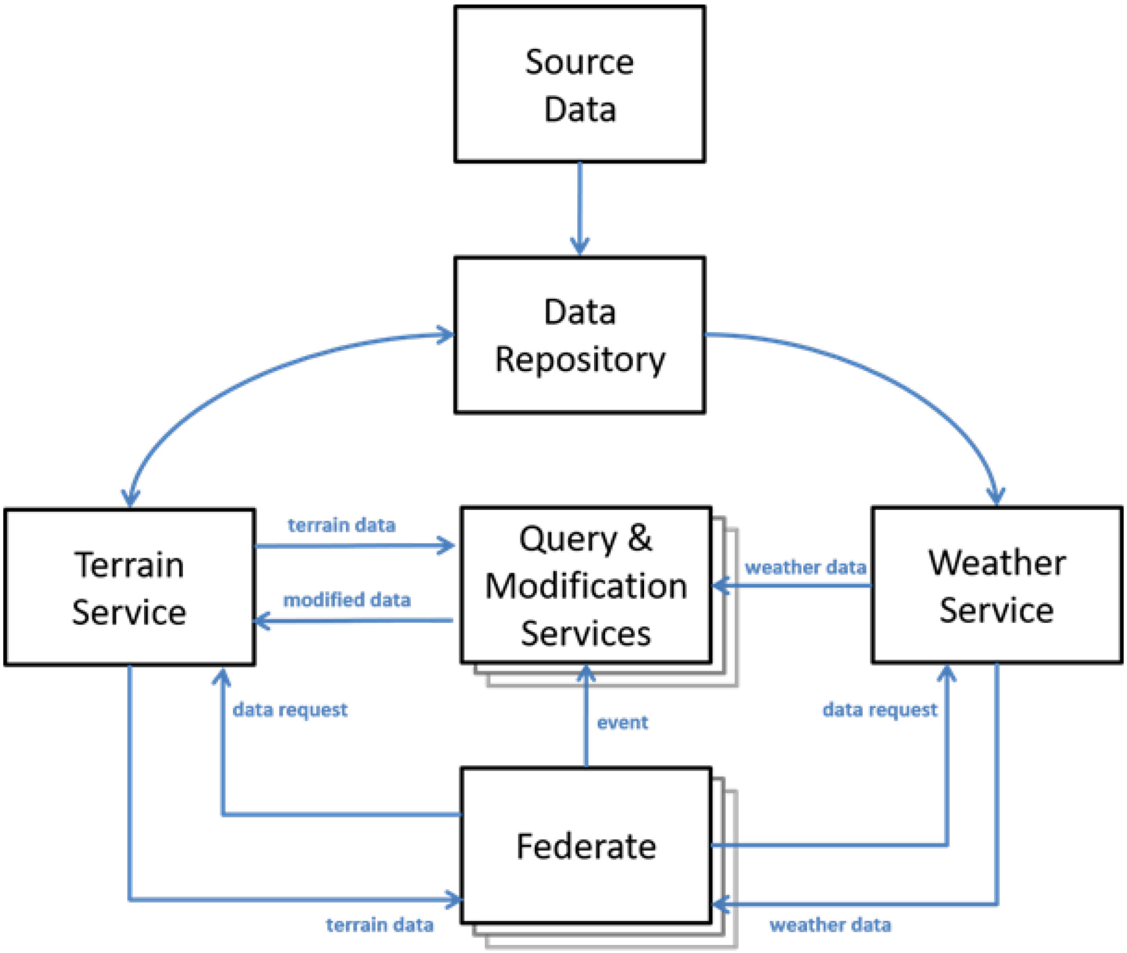

Figure 3-9: Conceptual Solution Architecture for DSE.

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Chapter 4 – DYNAMIC TERRAIN

4.1 INTRODUCTION

This chapter discusses which aspects of dynamic terrain are considered by the MSG-156 TG to be most relevant for simulation exercises, which terrain data is involved in representing them and how such data can be distributed in distributed simulation exercises.

4.2 DYNAMIC EFFECTS AND THEIR SIMULATION METHODS

The dynamic terrain effects considered most important to be included in distributed simulation exercises and the simulation methods to represent these effects are discussed in this section.

4.2.1 Deformation of the Terrain Surface

In the real world, deformations of the terrain surface can be caused by many different sources. In the TG's view the most relevant sources of terrain deformations for simulation exercises are:

1) Explosions, resulting in, e.g., craters.
2) Extreme weather, resulting in, e.g., landslides, avalanches, or flooding.
3) Man made by combat engineering or construction works, resulting in, e.g., trenches, ramparts.

Smaller-scale effects, such as tire tracks, have not been considered in this study, although it is likely that they can be represented using a similar approach. The TG gave them a lower priority, because their impact on the simulated exercise is typically limited, while their technical requirements are high (in terms of resolution required to accurately represent them, and the potentially large volume of data to be communicated).

Simulation systems use various techniques to represent such terrain deformations, possible implementations are:

1) A decal texture, which overlays a visual representation of the deformation on the terrain, without modifying the actual terrain itself.
2) A pre-defined 3D model of the terrain deformation which is being positioned on the terrain when a deformation happens. For example, a 3D model of a crater can be placed where a detonation occurs. This approach does not modify the actual terrain itself.
3) Modifications to the terrain being calculated locally by the simulation system based on the event that causes the deformation. For example, a crater that is being calculated based on the location of a detonation and on the type of weapon that exploded. To ensure correlation between different simulation systems, the algorithms used to calculate the deformation could be standardized, so that everybody uses the same algorithm.
4) Modifications to the terrain that are centrally computed, and the resulting state of the terrain being distributed to participants in the exercise.

It is clear that the last two approaches to handle terrain deformations will ensure the most consistent result for the participants of the simulation exercise. The TG considered the last option, the centralized computation of modifications as the most promising, as any other approach will require lots of additional work, agreements and testing and verification to ensure correlation and prevent fair-fight issues. It is the objective of the TG to handle these events dynamically considering the following aspects:

1) The position and the form of the terrain changes are unknown a priori. No pre-processing shall be done.
2) All federates shall share and show the same result.
3) Craters and trenches shall be depressions in the terrain (i.e., actual changes to the elevation profile, not just visual representation).

A key technology for simulation systems to be able to handle terrain deformations in a dynamic way is that they can easily (re)generate their terrain representation during simulation execution after changes have occurred. This means that the terrain representation can no longer be static and prepared beforehand but has to be generated by the simulation system based on available data. This technology is often referred to as streaming terrain or online synthetic environment generation. Such technologies take the geographical source data, e.g., the elevation data, and generate the terrain skin from that during runtime. Terrain deformation result in a modification of this source data and thus require a regeneration of the representation.

A study into methods and architectures for provisioning dynamic simulation data repositories was undertaken as part of the UK SE Tower Simulation Composition and Representation of Natural and Physical Environments (SCORE) project (2014 – 2018) [1], [2]. This investigated the use of supporting datasets within simulation systems. A primary focus of this research was to investigate how a service-based architecture might enable a dynamic data system in which a terrain dataset stored within a central terrain server could be updated in real-time to reflect events occurring within a synthetic environment.

4.2.2 Damage of Features and Structures

Terrain features and structures can be damaged due to the same causes as the deformation of the terrain surface. These damages may have an influence on the visual appearance of them, but far more important is that they can also change their usability. A destructed bridge for example has a major influence on route calculations.

There are commonly two ways of dealing with damage to structures in simulation systems:

1) **Use of pre-defined damage states:** A traditional approach is to provide structures with several representations of damage states initially. The damage state of them is then shared within the federation, and each simulation system can switch to the appropriate representation of the structure, e.g., a building is provided with a normal, damaged and destroyed state and based on the vitality of the scenario entity that represents the building the right state is shown.
2) **Distribution of dynamically calculated damaged structures:** A central service calculates the damage of the structures and shares the results with the participants. Within the conceptual architecture this means a modification service determines the damages and then updates the representation of the structure in the Terrain Service.

The preferred solution of the task group is using a centralized service to calculate the damage to features and structures. As this is the best approach to ensure a consistent representation. But a hybrid solution can also be employed where the pre-defined damage states are linked to feature attributes in the Terrain Service that represent the functional state of the feature or structure. It is important however that the Terrain Service is the central place where this information is stored, and that structures and features are no longer added as scenario entities just to be able to damage them.

In many of the examples above buildings are used as features that are damaged. The same techniques can also be used to handle damage to bridges or roads. These not only have a visual effect in the simulation, but also an important effort on the navigational capabilities of entities in the simulation.

4.2.3 Trafficability

Dynamic changes to the terrain can have a big influence on the ability of vehicles to travel over the terrain. For example, bad weather conditions can result in muddy roads and affect the ability of vehicles to move. This is called the *trafficability* of the vehicles. Trafficability should not be confused with the *mobility* of the vehicles, which is their capability that permits them to move from place to place while retaining the ability to fulfil their primary mission [3]. Mobility is also influenced by damage to roads and bridges for example, as was discussed Section 4.2.2.

Trafficability is mainly influenced by the soil conditions of the terrain and the moisture level of the soil. Therefore, information about the surface type, soil type and soil moisture level should be stored as part of the representation of the terrain.

Dynamic changes to these attributes, caused by for example the weather, could then be made by each simulation system locally or be done centrally by a modification service. The preferred approach of the TG is to have a central service responsible for this, which stores the modified terrain attributes in the Terrain Service. The trafficability model can then retrieve these terrain attributes from a central location.

The final step in determining the trafficability of vehicle is to calculate what their trafficability is given the current condition of the terrain. This is typically presented as the maximum speed for vehicles traversing terrain. Many simulation systems nowadays feature some form of trafficability computation; however, this is typically done locally using static terrain data. To have consistent result and prevent fair-fight issues it is desirable that all vehicles in the simulation exercise used the same trafficability model, which means that this should be provided a central service as well, that all simulation systems can consume.

Simulation systems do have implementations of trafficability models, but a commonly used model for effects does not exist. The MSG-156 TG used a more operational model [4]. Within NATO a NATO Reference Mobility Model (NRMM) exists which does also include the aspect of trafficability. This model is typically used for more operational applications, like mission planning. AVT-327 is developing a Standardization Recommendation (STANREC) for the Next-Generation NATO Reference Mobility Model (NG-NRMM). Simulation is becoming more important in the work of AVT-327, so for the future it is foreseen that distributed simulation exercises might be able to benefit from the NG-NRMM model as well. The benefit of a Trafficability Service would be that the knowledge of the NG-NRMM model only has to be implemented in one central location in the distributed simulation.

4.2.4 Additional Dynamic Effects

Besides the three main effects the group investigated in detail, as described above, a few other possible dynamic effects could be considered for implementation in distributed simulation systems.

4.2.4.1 Dynamic Vegetation

Human introduced effects and extreme weather can be responsible for changes and destruction of vegetation as well, interesting examples of this are forest fires or storm damage affecting the mobility. The dynamic changes to the vegetation may influence the Line of Sight (LoS) as well as trafficability.

Technically the same solutions as for handling the damages of infrastructure and structures can be used. Therefore, the same solution concepts can be applied to make dynamic changes to the vegetation layer of the terrain data.

4.2.4.2 Features Persistent State for Degree of Freedom

Some features can have different states for elements of the structure, this is typically called a Degree of Freedom (DOF). Examples are drawbridges or barriers that can be in an open or closed state or in transition between those two states.

Technically these DOF states can either be represented as part of the model used for the structure, e.g., a DOF node in the OpenFlight model or they could be handled with different representations of the model that are switched based on conditions, similar to how the damage to structures can be represented. Both options have in common that the correct state or the value of the DOF must be managed dynamically in the simulation exercise. Just as for the damage to structure inclusion of this state information in the terrain data is a suitable approach to ensure that the state is represented consistently by all participants.

4.3 TERRAIN DATA AND DATA STRUCTURES

The required terrain data is divided into two categories of data:

1) **Raster data** is geographical data that is represented as a grid of values, where each grid cell describes a specific area of the real world. An example of this would be elevation data, where each grid cell describes the elevation of the terrain in that cell. But also, aerial imagery is typically provided as raster data, where each cell provides the color values of how that area of the terrain looks.
2) **Vector data** is geographical data where the terrain features are described using points, line, and polygons. Examples are a polygon that describes where a forest is, a line that describes where a road is and a point that describes the location traffic light. The vector features can have attributes that describe additional details of the features. For example, a road feature can have attributes to describe the width of the road or the material that the road is made from.

The following sections describe the typically layers of terrain data that are used to describe the environment and how they are used in the context of the dynamic environment.

4.3.1 Rasterized Data

4.3.1.1 Elevation Data

The dataset describes the elevation model of the mission area (Figure 4-1). Each pixel contains a floating-point value that can be transformed to an absolute terrain height according to the vertical projection information.

Elevation data is often stored in a Tagged Image File Format (TIFF) or GeoTIFF image. The Digital Terrain Elevation Data (DTED) format is also commonly used in the military domain, which on top of storing the elevation data also prescribes different levels each with a specified resolution.

Figure 4-1: Example of Elevation Data.

4.3.1.2 Digital Ortho-Photo

Aerial imagery is important for the visualization of the terrain, each pixel of the dataset describes the visual color of the terrain (Figure 4-2). Aerial imagery data is often stored in TIFF or GeoTIFF images.

Figure 4-2: Example of Digital Ortho-Photo.

4.3.1.3 Surface Types

This dataset describes the surface type of the terrain, for example if the surface is road, forest, or field. Each pixel provides a value that is used as an index to lookup the surface type. Surface type data is often stored in TIFF or GeoTIFF images.

A surface type raster can either be generated by rasterizing vector data that describes the surface type, but it can also be the outcome of analysis on raster aerial imagery data (Figure 4-3). The resolution of the raster data defines how small the details are that can be included. For example, in low resolution data it might be hard to represent a narrow road.

For a dynamic environment, the surface type data is important, as it influences the trafficability, especially the combination of weather and surface type is relevant in that case. Having the surface type data in the raster format instead of vector format can be more efficient for the trafficability calculations, especially if these have to be performed for many entities.

Figure 4-3: Example of Surface Type Raster.

4.3.1.4 Soil Types

This dataset describes the soil type of the terrain, for example if the soil is made of sand, clay, or rock. The difference with the surface type layer described before is that the surface type describes what is on the surface of the terrain, while the soil type layer describes the material the topsoil layers consist of. Each pixel provides a value that is used as an index to lookup the soil type. Surface type data is often stored in TIFF or GeoTIFF images.

For a dynamic environment, the soil type data is important, as it influences the trafficability, especially the combination of weather and surface type is relevant in that case. Having the soil type data in the raster format instead of vector format can be more efficient for the trafficability calculations, especially if these have to be performed for many entities.

4.3.1.5 Surface Moisture

This dataset describes the moisture level of the terrain surface (Figure 4-4). The values of the pixels represent the amount of moisture in the data. Compared to the surface type and soil type layers described before, this layer has a more dynamic nature, as the moisture level will vary with time while the scenario is progressing, especially when the weather is dynamic. This means that this dataset will be updated frequently while the simulation progresses.

Figure 4-4: Example of Soil Type Raster.

For a dynamic environment, the surface moisture data is important, as it influences the trafficability. Having the soil type data in the raster format instead of vector format can be more efficient for the trafficability calculations, especially if these must be performed for many entities (Figure 4-5).

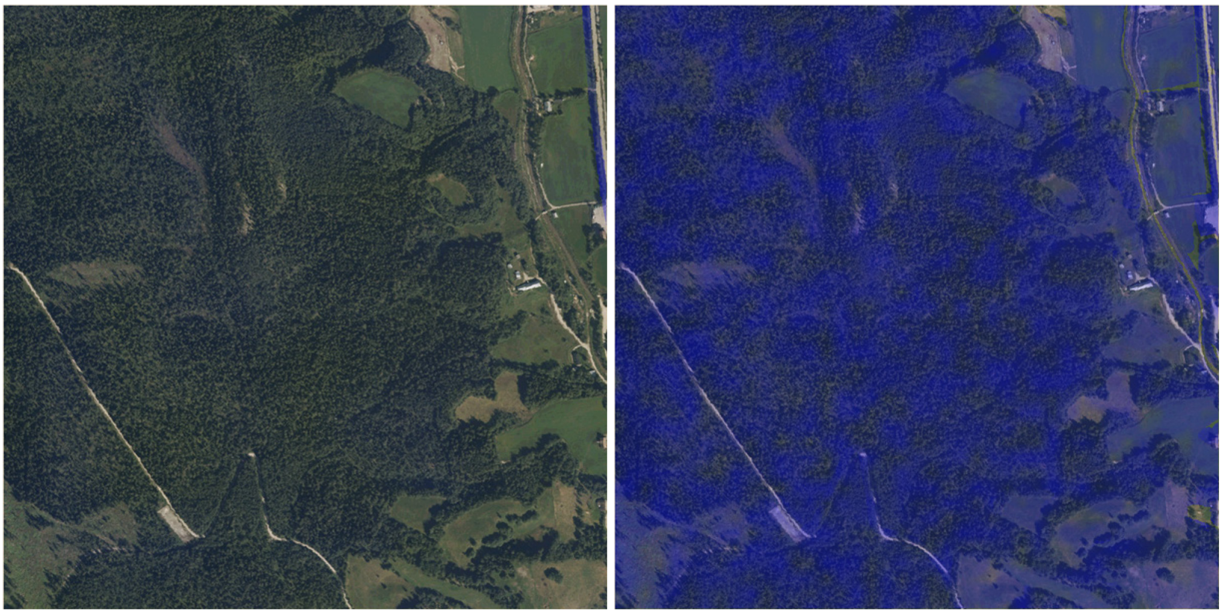

Figure 4-5: Example of Surface Moisture Raster at Different Moments in Time.

4.3.2 Feature/Vector Data

4.3.2.1 Road Network

The road network is represented as an attributed set of linear features (lines) (Figure 4-6). The attribution contains information about road type, surface, and status. In a DSE especially the status attribute can be used dynamically e.g., operational versus impassable to indicate that damage to the road impacts the usability of a segment.

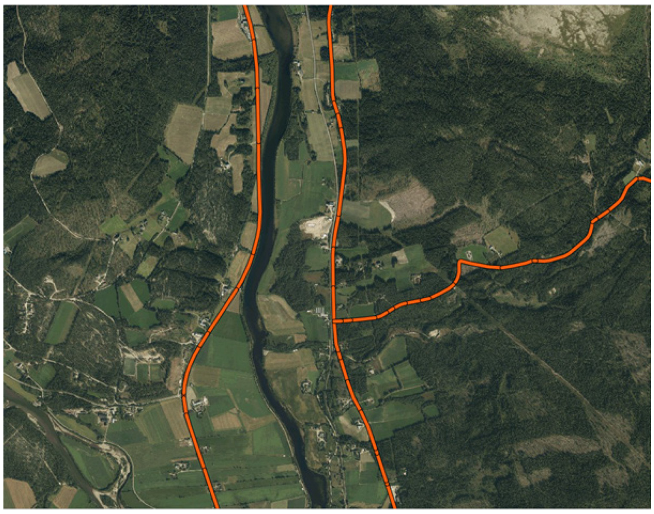

Figure 4-6: Example of Road Features.

4.3.2.2 Surfaces

The surfaces layer contains aerial features describing the surface types of the area (Figure 4-7). Attributes of the polygons describe the surface type that it has. It is a vector representation of the raster surface type layer, see Section 4.3.1.3. Depending on the available source data the vector surfaces layer can either be a vectorization of the available raster data or it can be based on available data from a geo office, like cadastre data.

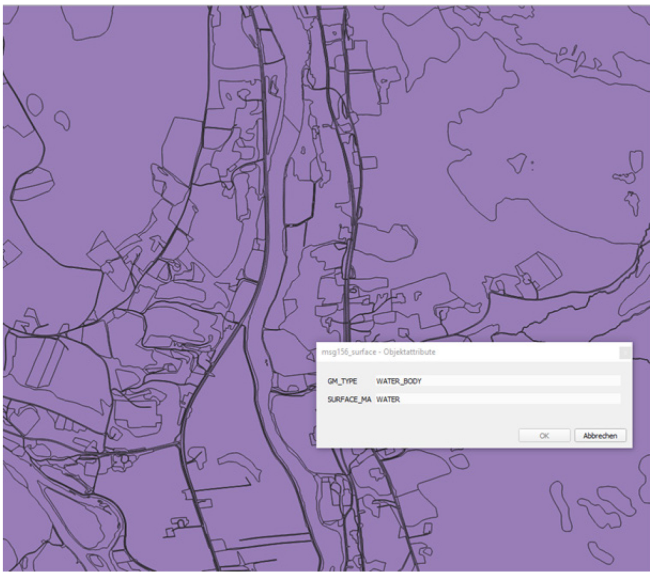

Figure 4-7: Example of Surface Features.

4.3.2.3 Vegetation

The vegetation layer contains areal features describing where there is vegetation (Figure 4-8). The attributes describe additional details like vegetation type, density, or height.

Figure 4-8: Example of Vegetation Features.

4.3.2.4 3D Models and Textures

This dataset provides the 3D models of features like buildings and bridges (Figure 4-9). These are relevant to be able to give a visual representation in the simulation systems of these structures. The de-facto standard for 3D models in most simulation systems is the OpenFlight standard, while many systems also use their own proprietary formats. Together with the geometry of the model, textures are provided that determine the visual looks. It is unsure if the OpenFlight format is also suitable for streaming the environment or for making dynamic changes to it.

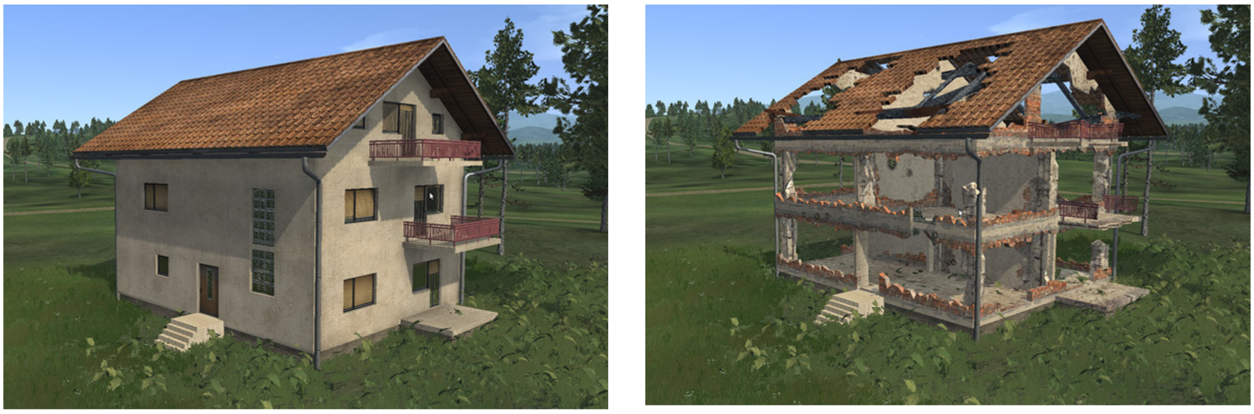

Figure 4-9: Example of Building with Undamaged (Left) and Damaged (Right) State.

The 3D models are placed in the environment by vector point features that specify the location on the terrain where they are placed, as well as their rotation and scale factor. These additional details are provided as attributes.

In a dynamic environment the representation of the model can change, as discussed in Section 4.2.2 about damage to structures. This can be done either by replacing the entire 3D model with a different representation or by setting a switch to show another representation, for example a damage state.

4.4 DATA DISTRIBUTION

This section discusses the techniques and standards that are available for distribution of the terrain data layer described in Section 4.3.

4.4.1 Raster Data

One option for sharing the raster data is to share the GeoTIFF files in which the data is typically stored. But this approach is mainly suitable for sharing the data before the simulation exercise. A more interesting approach to distribute the raster data during the simulation is the use of OGC standards for streaming raster data. These standards are discussed in more detail in the sections below.

4.4.1.1 Web Coverage Service (WCS)

4.4.1.1.1 Standard Functionality

The Open Geospatial Consortium (OGC) Web Coverage Service (WCS) [5] is a web standard for the discovery, request, and retrieval of raster-based geospatial data that contains digital geospatial information representing space and time-varying phenomena. The standard defines a number of mechanisms in the form of RESTful web requests that enable a client to access multi-dimensional (rasterized) coverage data in forms that are useful for both client-side rendering and as input into scientific models.

The WCS protocol allows clients to retrieve subsets of data choose portions and different resolutions of a server's information holdings based on time spatial constraints and other query criteria. The WCS standard can deliver data in the original resolution and format in which it is stored by the WCS service, however, a client is also able to request (through providing additional WCS request parameters) that the data is processed by the WCS service prior to transmission to the client. This allows a client for example, to request data that is resampled. The standard also provides (through a transactional extension) a means by which a client can provide new or updated data to the service. Due to its capability in handling a wide range of multi-dimensional raster formats, its flexibility in providing resampled data, and its alignment with MSaaS aims and approaches, the WCS standard was selected to provide all the data that is described in the section Rasterized data.

4.4.1.1.2 Dynamic Extension

As the exchange of the dynamic data should work completely service-based, the updated data has to be transferred by an internet protocol as well. The OGC provides an extension of the WCS Standard for that, called the transaction extension [6].

The standard provides the interfaces for sending update to the hosted data layers. Technically there are two ways of doing that. The first is a binary body in an Http-POST request and the second is to provide a download link, which can be used by the receiving part to download the data. The OGC-Specification uses the second option, due to practical reasons the TG opted to use the first option since it makes it much easier for modification services to provide updated data. For the second approach there needs to be a storage where the services can put the data and the terrain service can download it from.

The execution of an update consists of four steps:

1) Federate or modification service generates the updated content.
2) Update-request including the new data is sent to the terrain service.
3) Terrain Service responds ok when the data has been stored.
4) Federate sends update notification to the federation.

4.4.1.2 Web Map Service (WMS)

The WMS service [7] delivers geo-referenced imagery stored in the terrain service. This can be every image layer which the environmental dataset contains.

In any case the service delivers a raster image of the requested area, which can be used in any application. As this service is a well-known standard, many applications deliver connectivity to it off-the-shelf.

Basically, the WMS can deliver the same data as the WCS. Since it represents the data as a color image bit however, it is mainly suitable for delivering the aerial image and the map layer. When used for other layers, like the elevation layer, information is lost when transforming it to a color image and that means the result is not useable for simulation systems anymore.

4.4.2 Feature/Vector Data

Vector data is often stored as ESRI Shapefiles, so one approach to distribute the data is to share these Shapefiles with all participants. This approach is mainly feasible to share the data before the simulation exercise; for sharing the data during the simulation exercise the OGC WFS standard is more suitable.

4.4.2.1 Web Feature Service (WFS)

The WFS is a service [8] for interchanging feature data including all semantic as well as geometric information in a standardized way. It uses the Geography Markup Language (GML) format to deliver the feature data and application can request data for a specific geographical region or using specific attribute filtering. The GML format is XML-based, which makes it easy to read and implement in simulation systems.

The WFS standard can provide all data that is described in the section about Feature/Vector data.

4.4.2.2 Data Model

The WFS standard provides a way to distribute the feature data and its attributes. But to make it easier for simulation systems to consume this data not only the distribution of the data needs to be standardized, but also how the semantics of the data is defined. This part is covered by the data model that is used for the feature data.

Various standards exist in the GIS and M&S domain which provide such data models or parts of them. These include:

- DGIWG Feature Data Dictionary (DFDD) and Feature and Attribute Coding Catalogue (FACC) are standards for attributes and enumerations that are often use by military geographic offices in the feature data product they provide.
- The Synthetic Environment Data Representation and Interface Specification (SEDRIS) standard [9] provides all the building blocks to make a data model. And the SEDRIS Environmental Data Coding Specification (EDCS) [10] provides a standard for attributes and enumerations.
- SISO Reuse and Interoperation of Environmental Data and Processes (RIEDP) [11] provides an abstract reference model for a terrain dataset. The RIEDP standard will be expanded with another document that covers how the semantics of a RIEDP dataset should be described.

For the data model to work with the WFS standard a GML data model, which covers the simulation specific content, has to be agreed upon. The German SES implementation, which was used in earlier NMSG and German projects, uses a data model that is based on the SEDRIS standard.

4.4.3 Content Data

Besides feature data, the Terrain Service should also be able to provide content data. This includes the 3D model geometry to represent structures and the textures that are used for their visual representation. It is important the simulation specific aspects of the content are supported like:

- Multiple Levels of Detail (LOD) to vary the complexity of the structure representation based on distance or simulator capabilities;
- Degrees of Freedom (DOF) for specify the state of moveable parts, like a gate, door, or barrier; and
- Different representations based on the damage state.

Besides that, it should be possible to have the content fully geo-referenced, so that the location where the object is placed can be stored. Furthermore, to allow dynamic interactions with the content there should be a unique ID assigned to each of them so that the simulation federates can refer to a specific instance of the structure.

Different approaches can be used to distribute the content:

- Provide them in the standards that are used by the simulation systems and have them accessible in a central service so that all participants can download them. The de-facto standard for 3D models in simulation systems is the OpenFlight standard [12].
- The WFS standard does also support the transfer of 3D data and the data model used can take the specific requirements for LOD, DOF and damage representations into account. This approach has been demonstrated in the German SES implementation.
- Within the game industry streaming 3D model content is becoming more common as well. Formats like GL Transmission Format (glTF) [13] do support this. However, these solutions do not always cover all specific aspects like LOD, DOF or damage representations.

Since support for 3D data via WFS and support for the new standards from the game industry is still very limited in current simulation systems, the usage of the OpenFlight format [12] is the most practical solution for the near future. However, there is a need for a standard for 3D content that offers better support for streaming content and for making dynamic changes to the content. Once such a standard is available it should be considered as an alternative for OpenFlight. It might be needed to extend a standard from the game industry based on the M&S specific needs.

4.5 HANDLING DYNAMIC EFFECTS

As discussed in Chapter 3, the TG decided to develop a MSaaS-based solution architecture for the DSE. This section provides an example of how dynamic effects are handled in such an architecture. An IED explosion and the resulting crater in the terrain is taken as example.

Figure 4-10 to Figure 4-15 illustrate how the federates and services work together to achieve a dynamic effect in the foreseen DSE architecture. The example covers the explosion of an IED and how a resulting crater is made in the terrain.

The following components are involved in that process:

1) The Federation as a whole. Single federates within the federation may trigger effects and other federates may receive their outcome.
2) The Terrain Service which collects and distributes the topical terrain at any stage of the simulation.
3) A Modification Service that receives the parameters of the detonation event, calculates the impact on the elevation model and updates the elevation model of the Terrain Service.
4) The Notification Broker for informing the federation about the necessity of an update.

The process below shows how the terrain representation is updated based on the detonation event of the IED and which role the various services play in that.

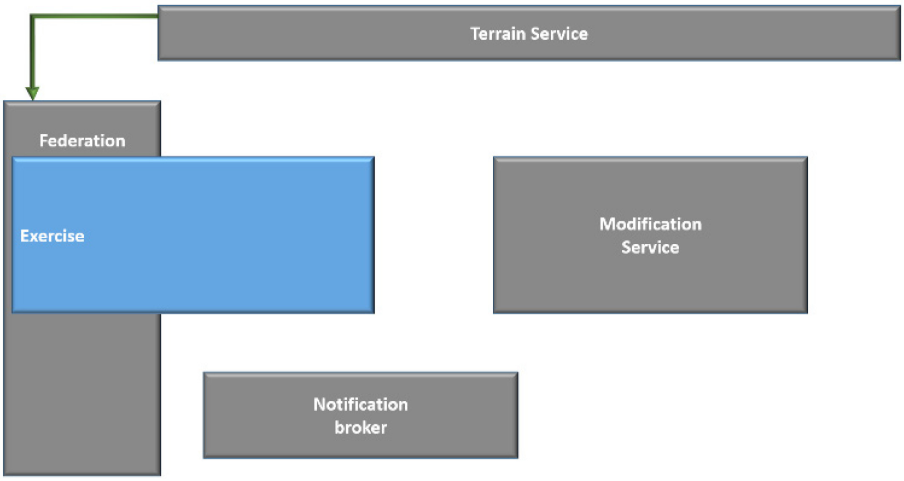

Figure 4-10: Initial Terrain Data Supply.

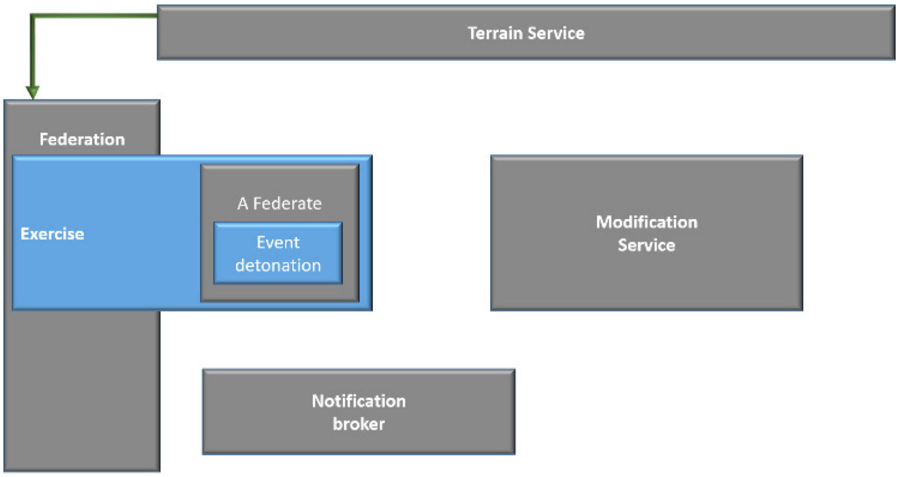

Figure 4-11: Detonation Event.

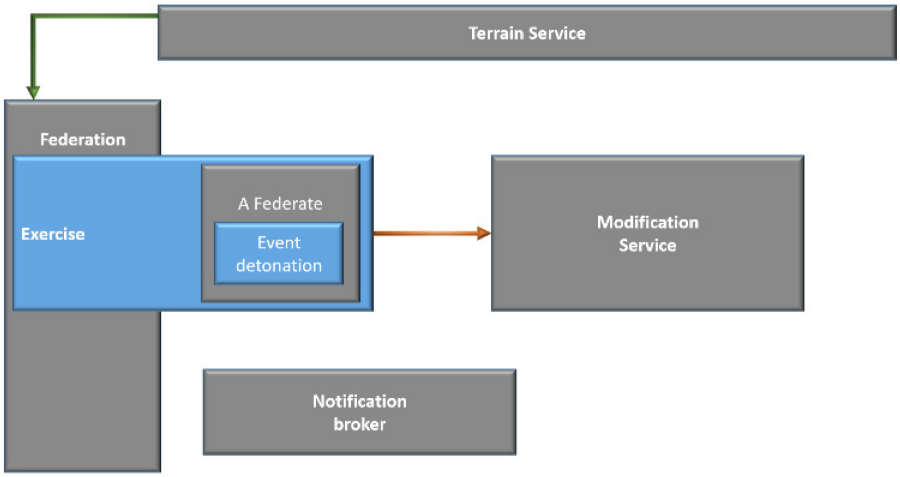

Figure 4-12: Activate Modification Service.

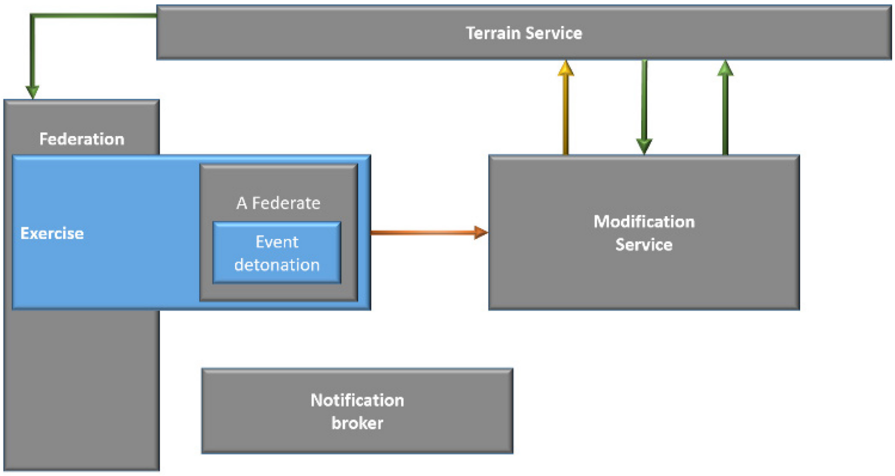

Figure 4-13: Update Terrain Representation.

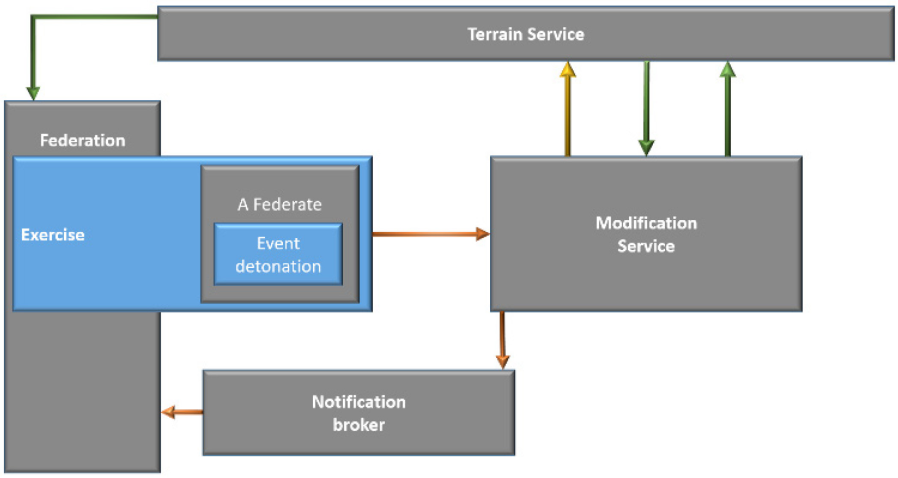

Figure 4-14: Update Notification.

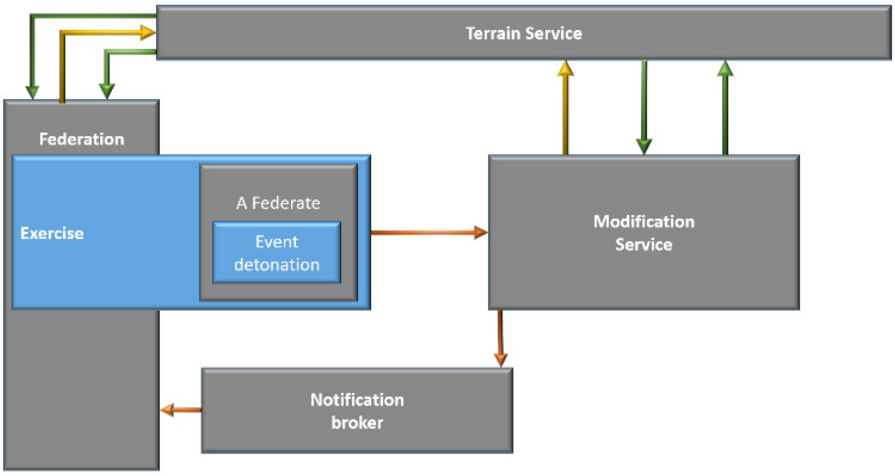

Figure 4-15: Update Terrain Representation in Federate.

4.5.1 Initial Terrain Data Supply

Before or at the start of the simulation exercise all federates will request the terrain data from the Terrain Service.

4.5.2 Detonation Event

During the exercise, a federate triggers the event of an explosion. This event is accompanied with a set of parameters describing the exploded devices, the position of the detonation and so on.

4.5.3 Activate Modification Service

The detonation event is received by the Modification Service, and this triggers the process to update the terrain representation.

4.5.4 Update Terrain Representation

The Modification Service requests and receives the current terrain data from the Terrain Service.

Using that data, it calculates the changes due to the detonation and provides this updated data back to the Terrain Service.

The Terrain Service will store this data as the new current state.

4.5.5 Update Notification

After the Modification Service has received the response of the Terrain Service that the update has been stored successfully, the Modification service informs the Federation via the Notification Broker that a change has occurred.

4.5.6 Update Terrain Representation in Federate

All federates receive the change notification message. Based on the content of the notification they can determine if they are interested in this update. If so, they will request the new terrain data from the Terrain Service.

4.6 REFERENCES

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Chapter 5 – DYNAMIC WEATHER

Defence operations are performed in environments where weather can have an impact on operational capability, including platform and systems behavior. Examples include the effects of rain on the terrain surface which can affect ground vehicle mobility and the effects of cloud formations/precipitation on air platforms and airborne sensors, such as Unmanned Aerial Systems (UAS), used for reconnaissance activities.

This chapter discusses which aspects of weather are most relevant for simulation exercises, which sources of weather data are available for these exercises and which techniques can be applied within the simulation systems to represent the weather.

5.1 SIMULATION USAGE OF WEATHER DATA

To enable more effective use of synthetic environments for applications including defence training, common methods and processes are required to consume weather data and represent weather effects in a consistent manner across simulation systems. The main usages are:

1) Visualization of the weather in out-of-the-window and sensor images of virtual simulation systems, so that the operator of the simulation (i.e., the trainee/training audience) can observe the weather, which may influence the decisions that the operator makes, e.g., a pilot might choose to fly around a thunderstorm cloud that he sees ahead of him.
2) Effects of weather data on the dynamics of simulated platform vehicles in both virtual and constructive simulations, e.g., the effect of wind on the flight path of an air entity or the effect the temperature has on the performance of an engine.
3) Effects of weather on the state of the terrain, which can subsequently affect the trafficability of ground-based entities, e.g., changes to the conditions of unpaved roads due to rain.

For each of these usages above it can be identified which parameters of weather data are most relevant. This is partly based on work carried out in the UK SCORE project [1]. Table 5-1 gives this overview.

Depending on the simulation component it will differ over which area these weather parameters are needed. For example, to determine the effect on the dynamics of an entity the weather parameters are needed at the location of that entity. But an image generator that visualizes what the operator sees will be interested in the weather data over the entire field of view. And to realistically simulate the effect of the weather on a sensor the weather data along the line of sight between the sensor and the target is of interest. This means that different ways to query the weather data might be needed, based on the needs of the simulation system.

Table 5-1: Relevant Weather Parameters for Different Usages.

Weather Usage	Relevant Weather Parameters
Visualization	Clouds Visibility/Fog/Haze Precipitation Wind speed and direction (for movement of clouds, waving of flags, etc.) Temperate (affects IR sensor image) Humidity (affects sensor image)

Weather Usage	Relevant Weather Parameters
Platform Dynamics	Wind speed and direction Precipitation Temperature Pressure Air Density
Terrain State	Precipitation Temperature

5.2 SOURCES OF WEATHER DATA

To be able to represent realistic weather in simulation systems the MSG-156 Task Group investigated options for accessing and processing real-world weather data to provide representations of weather and effects of weather in distributed simulations.

Real-world weather data is widely available in either live data streams or as historical data. Live streams of weather data are often subject of commercial agreements whereas historical data more often can be obtained freely. Authorities responsible for delivery of live weather data are local, regional, or national meteorological offices. Potential (open-source) meteorological field suppliers for the next-generation training simulation may therefore include, but are not limited to:

- UK Meteorological Office [2];
- Norwegian Meteorological Institute [3];
- Météo France [4];
- The Royal Netherlands Meteorological Institute (KNMI) [5]; and
- National (USA) Oceanic and Atmospheric Administration Service [6].

Both live streams and historical data can also be obtained at international authorities like the European Centre for Medium-Range Weather Forecasts (ECMWF) [7] and the NOAA (National Oceanic and Atmospheric Administration) [6].

Initial investigations into sources of weather data, which includes the UK Meteorological Office, identified the source data as having too low a spatial and temporal resolution to be directly consumed into simulation systems, e.g., image generation systems. Weather data for large areas typically comes in a gridded format. Common grid sizes are 2.5 x 2.5 kilometers, 11 x 11 kilometers, and 25 x 25 kilometers. While this is considered high resolution for weather applications, having a realistic representation in a vehicle simulation might require a higher resolution. The temporal resolution of weather data is often 1 hour, while for simulation purposes the weather requires a finer resolution.

There is no single spatial or temporal resolution that is suitable for all simulation components as it is dependent on the task being performed. It is also not feasible to generate weather data from a full model at the resolution required by a visual system, since that requires a lot of computing resources. This means interpolation between the available data elements is required. For correlated cloud cover to be rendered within an image generation system, a high-resolution cloud coverage map is required. The highest resolution weather data provided by the UK Meteorological Office was ~1.5 km and as this requires some procedural up sampling there is the potential for lack of correlation across simulations that would affect ‘fair fight’.

To solve this, it was decided that the up sampling should be performed in a central place, such that the same procedurally refined dataset can be provided to multiple clients based on the original source data.

Different levels of fidelity could be used for such refinements:

- Simple bilinear interpolation with added noise.
- More advanced refinement algorithms, including use of statical models.
- A full weather model running in the simulation (in the future, depending on processing power and time available).

The most common formats for the exchange of weather data are GRidded Information in Binary (GRIB) and NETwork Common Data Form (NetCDF) [8]. Although there are differences between the two formats it is possible to convert GRIB to NetCDF and vice versa. Both standards can contain meteorological parameters like cloud cover level, humidity, horizontal and vertical wind direction, and speed, and (ambient) temperature.

NetCDF is a file format for multi-dimensional scientific data such as temperature, humidity, pressure, wind speed and direction. These fields can be displayed through both spatial and temporal dimensions. NetCDF data, as defined by the ArcGIS Help tool, are:

- Self-describing, meaning that a NetCDF file includes information about the data it contains, such as when data elements were captured and what units of measurement were used.
- Portable, or cross-platform, in that a NetCDF file created on one type of operating system can often be read by software on another type of operating system.
- Scalable, such that a small subset of a large NetCDF file can be accessed efficiently without reading the entire file.

One of the key benefits of using the NetCDF format is that it meets the requirements of the Open Geospatial Consortium (OGC). Meeting these standards is a key benefit for NetCDF files and ultimately their end-use in visualization systems. The benefits of meeting these standards are because of the increased open-source / public and defence use of these standards. The Defence Geospatial Information Working Group (DGIWG, 2019) is seeking to standardize all geospatial data (geospatial, meteorological, oceanographic, and geospatial aero-nautical information) across allied defence organization nations. Generally, the standards to which they align to are those used in the public domain (ISO, 2019) which is in-line with increasing coalition interoperability and a key objective for MSG-156.

The features of NetCDF files means future requests to weather data providers should be requested in NetCDF format. Exploring further open data sources that have not been considered as potential meteorological field providers should be considered against the training simulation / synthetic environment requirements. Such requirements include:

- The time intervals at which the meteorological parameters can be supplied – the MSG-156 discussion has considered 15-minute intervals would be optimal for the highest simulator requirements.
- Geo-Specific Fidelity – the resolution of the supplied meteorological fields over the particular area. For example, the UK Meteorological Office may supply excellent meteorological fields over the UK, but reduced resolution over Europe.
- Specialized meteorological fields such as ice cover on lakes may only be provided by national specific data providers which may have implications for which data provider is used, given the training simulation.
- Data formatting – in which format is the meteorological data provided? Is the file type suitable? Is the file type ASCII or NetCDF?

5.3 SIMULATION METHODS AND DATA STRUCTURES

5.3.1 Cloud Representation

When it comes to the representation of clouds in simulation systems different approaches are used. It depends on the system requirements and technical capabilities of the simulation system which approach is used. Common ways to represent the clouds are:

- **Clouds layers:** Based on information about the base height, thickness, cloud type and cloud coverage the system will show a representative cloud layer. The benefit of this approach is that little data must be exchanged about the clouds between the systems. But the downside is that the simulation systems have a lot of freedom on how to represent the clouds (e.g., different texture to represent a cloud type) and when the cloud coverage is not fully overcast it is hard to ensure that the gaps in the clouds are correlated between different systems.
- **Individual cloud object:** When specific clouds need to be positioned more accurately many systems do also support the creation of cloud objects. These can for example be used to place thunderstorm clouds. Typically, these individual clouds are specified based on a location, or a rectangle and the simulation then have to create the 3D representation within this bounding area. Many systems will use a particle system to generate these clouds. Compared to the cloud layers this give more control over where the clouds are positioned. A downside of this method is that more data needs to be distributed for each cloud and for many systems it also applies that they can only render a limited number of these individual clouds.
- **Raster-based clouds:** In this approach the simulation system receives a raster images of the cloud coverage and from this data a 3D representation of the clouds is generated. The benefit of this approach is that it is easier to ensure correlation in the shape of the clouds and where gaps appear. The downside is that more data needs to be distributed and that not all simulation systems are technically capable to handle such raster input.

Given that in a distributed simulation various system will participate in, including both state-of-the-art and legacy systems, it is likely that in the near future a mixture of the different cloud representations has to be supported. In that case the weather service, as the central location that provides the weather data, should ensure that the various representation correlate as much as possible. So, for example when the weather service provides a raster cloud coverage representation it will ensure that the individual clouds that are also served correlate with this raster.

As mentioned in the descriptions above, when generating cloud layers or individual clouds the simulation systems have freedom to determine where gaps in the clouds show or how a 3D cloud exactly looks. To reduce the correlation differences, it could be considered to have a set of agreed upon algorithms that all simulation systems can use. When seeding-based deterministic algorithms are used it is possible to generate the same "random" clouds on different systems. These approaches are commonly used in games as well. And having such deterministic algorithms could also reduce the amount of data that needs to be distributed between the different systems.

5.3.2 Standards to Exchange Weather Data

Although it is not common in current distributed simulations to exchange weather data, standards do already exist that allow the distribution of weather-related data. The most notable of these are:

- Common Image Generator Interface (CIGI) is a standard for the communication between the simulation and the image generator. As such it allows weather related data to be send to the image generator, so that a visual representation of this can be generated. Weather parameters can be provided globally or for a specific region, e.g., a polygon. The parameters include the atmospheric conditions, visibility, precipitation, cloud layers and individual clouds.

- Distributed Interactive Simulation (DIS) includes a number of PDUs that can be used to distribute environmental data. These include the Environmental Process PDU and Gridded Data PDU. These PDUs can be used to distribute weather data, but support for these PDUs is not widespread in current simulation systems.
- High Level Architecture (HLA) allows the distribution of weather data as well, but the RPR-FOM does not include weather data by default. Therefore, work is ongoing to extend the NATO Education and Training Network (NETN) FOM with a module for METOC data. This development is being coordinated by MSG-163, but MSG-156 did provide input for this FOM and the current version of the METOC FOM was used in the concept demonstration of MSG-156. The NETN METOC FOM includes many of the concepts from the CIGI standard.

5.3.3 Distributing of Raster Data

When weather data for a bigger area must be distributed it is often most efficient to share this data in the form of a raster. For example, to distribute the temperature or wind distribution over a given area. However, it is not recommended that standards such as HLA be used for the transmission of large datasets such as raster data. This is because much of the data that us transferred within an HLA federation is time-sensitive in its nature, for example, notification of a munition detonation within a region that impacts a number of federates must be delivered to those federates such that no delay is observed in the federates ceasing to operate after the detonation has occurred. The Runtime Infrastructure (RTI) that supports an HLA federation is responsible for ensuring this timely delivery of simulation data. It is expected that using the same transport mechanisms for large quantities of raster data would have a latency impact on the delivery of simulation information, and raster data is in most cases not as time sensitive as simulation data. Therefore, the task group recommends using OGC standards for the distribution of weather raster data for big areas. These are the same methods as discussed in Chapter 4 for the terrain data. A weather service should thus implement an OGC WCS interface as well, so that simulation components can request the weather data in the form of a raster for a given area.

5.3.4 Distributing Base or Derived Weather Data

Theoretically the variation of the atmospheric conditions (temperature, pressure, humidity, etc.) provided within the weather dataset could describe the entire weather. For example, wind is the result of a pressure difference between two locations and clouds are formed as water droplets condensate. But this is not how weather is simulated in simulation systems. Instead of sharing the base atmospheric conditions, it is common to share the derived weather phenomena, like wind or clouds. The task group has discussed if sharing the base atmospheric conditions would not be a better strategy, but concluded that this is not the case due to:

- The fact that a lot more data would have to be shared, it would be a huge four-dimensional grid of data to share.
- Available sources of weather data also include derived weather phenomena, like clouds and wind, so it makes sense to align with these sources.
- Simulation systems are not designed to simulate the weather from the base atmospheric conditions; for the application of the simulation only the derived weather effects are relevant.

However, it is important to note that many of the base atmospheric conditions align with weather parameters that are required by federates within the system. Therefore, whilst it is not recommended to share the large multi-dimensional base data set, there are sub-sets of parameters within the data set that are shared along with the derived weather conditions. One example of this is atmospheric pressure which is provided within the base data as four-dimensional data (in a time-based 3D grid) but is provided to federates as a 1-dimensional sample taken from a 4D location specified by a federate.

5.3.5 Real-World Correlation

When it comes to the correlation of the weather data in a distributed simulation exercise, the most important aspect is that all participating systems perceive the same weather. Whether the represented weather does also correlate with the real-world weather is often less important. Therefore, it is important to ensure that all simulation systems can use the same source data of the weather and ideally this weather data would be distributed within the simulation exercise from a single service, e.g., a weather service.

5.4 REFERENCES

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Chapter 6 – A DSE ARCHITECTURE FOR DISTRIBUTED SIMULATION

This chapter describes the final architecture that MSG-156 has defined to achieve a dynamic synthetic environment in distributed simulations. First, the complete architecture will be described, after which each component is described in more detail, including data flows and interactions. Finally, how correlation is facilitated by this architecture is discussed.

6.1 DSE ARCHITECTURE

In Chapter 3 the conceptual architecture the task group started with was described. The discussions about the specific characteristics of dynamic terrain (Chapter 4) and weather (Chapter 5) have let to this final architecture that the task group proposes to achieve a correlated dynamic environment in distributed simulations. Figure 6-1 shows this resulting architecture. In this architecture, five different types of components are identified:

- **Environment Data Services** provide environment data to the other components in the architecture. These are the Terrain Service and Weather Service.
- **Environment Modification Services** make modifications to the terrain data. These services provide modified terrain data to the Terrain Service. Two primary sources of modifications are identified: 1) The weather; and 2) Events caused by simulation federates. For each of these types of modifications Interaction Modification Services are included. It should be noted that various instances of such services can be included in a federation, each tasked to process changes caused by specific events or on specific terrain data layers.
- **Environment Consuming Services** use the terrain data to provide a shared service to federates in the simulation. Examples of this are a Trafficability, Sensor Performance or Line-of-Sight Service.
- **Supporting Services** provide supporting functionality that federates, or services need to perform their tasks.
- **Simulation Federates** provide the virtual and constructive simulations that together form the distributed simulation.

Figure 6-1 also shows the main data flows between the different components. Each type of data is indicated with a different color:

- Terrain data (dark green);
- Modified terrain data (green);
- Weather data (blue);
- Change notification, from component that introduced the change to the broker (orange) and from the broker to a user of environmental data (yellow); and
- Simulation events (red).

The DSE architecture as described in Figure 6-1 is still abstract in the sense that it does not list the specific services that are needed to have a dynamic environment, it instead lists the various types of services that are needed. Therefore, the task group also proposes a more concrete architecture that lists the various services that are required to achieve a dynamic synthetic environment. This architecture is shown in Figure 6-2. This architecture shows the services that are needed to:

- Provide terrain data from a common source;
- Provide weather data from a common source;
- Modify the terrain conditions based on the weather;
- Modify terrain (craters) and buildings based on weapon events from the federates; and
- Have consistent trafficability for the federates.

Additional services could be required to simulate other dynamic aspects of the environment not considered in scope for the task group. For example, if crisis management applications require flooding to be simulated accurately, a service could be included determine where flooding occurs based on terrain and weather data. Additional query services could also be added, when federates require consistent information about the dynamic environment, e.g., a Line-of-Sight service.

In the following sections each of these components will be described in more detail.

For the communication between federates and the services two prime options are available. One is using HLA, which is the common way to federates within the federation to exchange their data. The second option is to use web-based techniques. To allow the flexibility to scale up services by running various instances in parallel, the TG has a preference to use web-based techniques for their communication, as with HLA it is not so easy to have various instances working together.

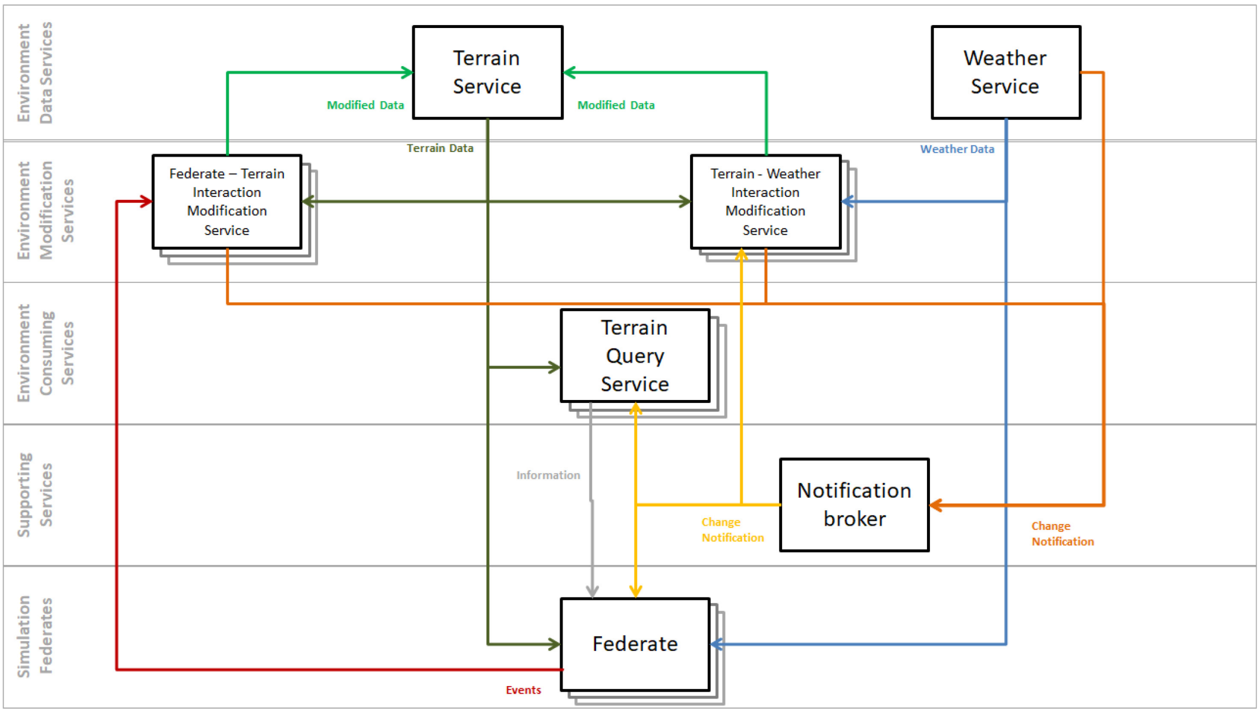

Figure 6-1: Architecture for a Dynamic SE in Distributed Simulation.

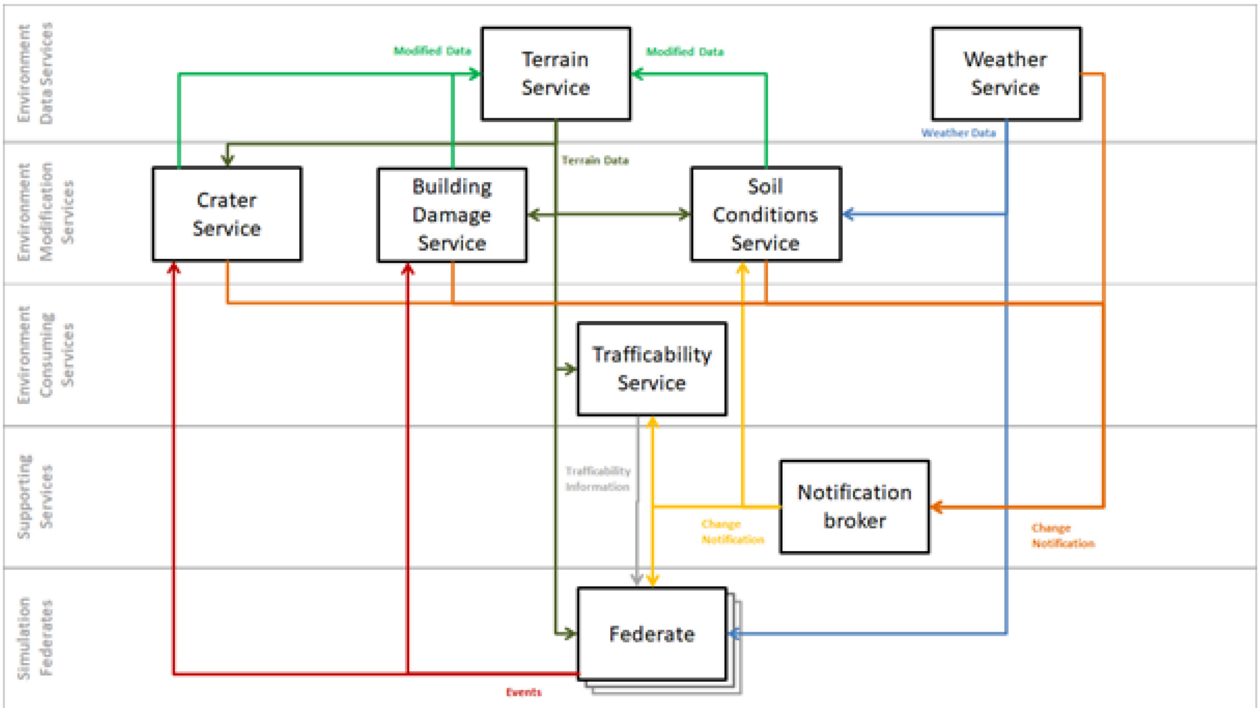

Figure 6-2: Architecture for a Dynamic SE in Distributed Simulation: Proposed Examples of Concrete Services.

6.2 ARCHITECTURE BUILDING BLOCKS

The different architecture building blocks shown in Figure 6-2 are detailed below, looking at the component's function, inputs, outputs, and data/format used.

6.2.1 Terrain Service

6.2.1.1 Function

Provide terrain data to simulation federates and services within the distributed simulation. The terrain service should be able to provide raster and vector data, and content. The following layers of terrain data should be included at least, while additional layers can be added based on specific requirements of the distributed simulation exercise:

1) Elevation data;
2) Imagery;
3) Surface material;
4) Soil conditions;
5) Vector data (roads, buildings, vegetation, etc.); and
6) Content (3D models and textures).

Federates and services will request data from specific layers for a specific area (geographic bounding box). Additionally, services can provide modified terrain data, which the terrain service will store as stacked changes on the original layer.

6.2.1.2 Inputs

- Geographical source data of the area that should be served by the terrain service;
- Modified terrain data generated by interaction modification services to be stored by the terrain service; and
- Requests to provide terrain data for a given area at a given resolution from federates and services.

6.2.1.3 Outputs

- Terrain data for the requested area to federates and services.

6.2.1.4 Data/Formats Used

The terrain service should use the OGC standards for providing geographical data over the web. This means that the following OGC services should be supported:

- Web Mapping Service (WMS) for providing images and maps;
- Web Coverage Service (WCS) for providing raster data; and
- Web Feature Service (WFS) for providing vector data.

To be able to update the terrain data dynamically the WCS-T (transactional) service should be supported by the terrain service.

An agreed upon data model should be used for the semantics and attributes of the vector data. An example of such a data model is the SEDRIS-based data model that was used in MSG-136.

For 3D models and textures there is no common standard yet to share this data from a service. A practical approach could be that the terrain service provides compressed files that contain the 3D model and its textures in the commonly used OpenFlight format.

6.2.2 Weather Service

6.2.2.1 Function

Provide weather data to simulation federates and services within the distributed simulation. The weather service should be able to provide the weather at a specific location as well as the weather data over a given area. The following parameters of the weather should be included at least:

- Atmospheric conditions (temperature, pressure, humidity);
- Wind (e.g., wind direction and magnitude);
- Visibility distance; and
- Clouds (including cloud density, base height, height, and type such as Cirrus, Cumulous, etc.).

The weather server should be able to serve real-world (historical) weather data, but it should also be possible for an instructor to overrule the weather or provide pre-scripted weather that matches the needs of the exercise.

6.2.2.2 Inputs

- Source weather data, see Section 5.2.

6.2.2.3 Outputs

- Weather data for the requested area to federates and services.
- Change notification to the notification broker when the weather data has changed due to a new time slice of the data being available.

6.2.2.4 Data/Formats Used

For simulation federates and services to request the weather state at a specific location, for example at the location of the entity being simulated, using the HLA standard with a METOC FOM is the most logical approach, as the federates will be connected on an HLA network already. The NETN FOM has a METOC FOM module in development that contains the data elements to request weather data and receive the weather data.

When weather data is provided for big areas, it is most efficient to provide it as raster data. Therefore, the weather service should support the OGC WCS interface to be able to request the weather as raster data for a given area and moment in time.

6.2.3 Crater Service

6.2.3.1 Function

Modify the terrain data by adding craters when weapon detonations occur. The crater can impact multiple layers of the terrain data:

- Elevation data, which should include the crater in the elevation profile.
- Imagery data, which visually shows the crater, e.g., visualize the dirt and soil that results from the crater.
- Vector data, which can be modified as the crater can modify for example the road network.

Based on the required level of fidelity for the simulation exercise the crater service can use different techniques to make the actual crater. A simple approach would be to have predefined crater templates that are applied to the terrain data, while a higher fidelity approach would be to calculate the shape of the crater based on the weapon characteristics and soil type.

For performance reasons it could be decided to split the Crater Service into multiple services, for example with a specific service for each layer of the terrain data that needs to be modified or with multiple services working in parallel to process the incoming events quicker.

When multiple services are used, the overarching Crater Service should ensure that change notifications are only send out when all aspects of the crater have been processed. So, for example, when there are separate services to modify elevation and imagery data, the change notification should be sent out when both these services have completed their work, as else inconsistent results can show in the federates.

6.2.3.2 Inputs

- Detonation event from federates; and
- Terrain data from the terrain service for the area where the detonation occurs.

6.2.3.3 Outputs

- Modified terrain data to the terrain service with the crater included; and
- Change notification to the notification broker when the terrain data has been modified.

6.2.3.4 Data/Formats Used

For the detonation event the standard detonation message from the RPR-FOM is used. This message contains the location of the detonation and information about the type of weapon that detonates. This is sufficient for the Crater Service to perform its task.

For the formats used for retrieving terrain data and storing modified terrain data see the section about the Terrain Service.

6.2.4 Building Damage Service

6.2.4.1 Function

Modify the building damage state when weapon detonations occur.

Depending on the desired level of fidelity multiple approaches can be used:

- Update the functional state attribute of the building in the vector data that places the building. This attribute uses discrete steps like normal, damaged, and destroyed. To each of these states a different representation can be connected in the 3D model used.
- Calculate the effect of the weapon detonation on the building and update the 3D model to show the damage created.

For performance reasons it could be decided to split the Building Damage Service into multiple services, for example with multiple services working in parallel to process the incoming events quicker.

6.2.4.2 Inputs

- Detonation event from federates; and
- Terrain data from the terrain service for the area where the detonation occurs.

6.2.4.3 Outputs

- Modified terrain data to the terrain service with the damage building included; and
- Change notification to the notification broker when the terrain data has been modified.

6.2.4.4 Data/Formats Used

For the detonation event the standard detonation message from the RPR-FOM is used. This message contains the location of the detonation and information about the type of weapon that detonates. This is sufficient for the Building Damage Service to perform its task.

For the formats used for retrieving terrain data and storing modified terrain data see the section about the Terrain Service.

6.2.5 Soil Conditions Service

6.2.5.1 Function

Precipitation falls on the terrain surface and is (partially) absorbed, changing the condition of the soil in a way that is dependent on many factors, such as the type of soil and the intensity of the rain. The condition of soil is relevant for the trafficability of a surface, but also for engineering operations. The Soil Conditions Service is responsible for determining the current state of the soil, given the current terrain and weather state.

6.2.5.2 Inputs

1) From Terrain Service:
   - Elevation: floating point raster, e.g., elevation in m.
   - Surface type: thematic raster of surface classes.
   - Soil type: thematic raster of soil classes.
2) From Weather Service:
   - Precipitation: floating point raster, e.g., precipitation in mm/h.

6.2.5.3 Outputs

- Soil moisture level: floating point raster, absolute value (mm) or relative (% soil saturation).

6.2.5.4 Data/Formats Used

For the formats used for retrieving terrain data and storing modified terrain data see the section about the Terrain Service.

6.2.6 Trafficability Service

6.2.6.1 Function

The primary responsibility of the Trafficability service is to provide a central hub for land-based simulators to request the maximum attainable vehicle speed, for a specific vehicle type, at a specific location and heading, and at the current scenario time. It achieves this by querying the Terrain Service for the current data of all relevant terrain layers and running a trafficability model to compute the (dynamic) speed-made-good.

6.2.6.2 Inputs

1) From Terrain Service:
   - Elevation: raster data.
   - Soil type: raster data.
   - Soil moisture level: raster data.
   - Update time.
2) Notifications of changes to terrain layers from the Notification Broker.
3) API requests from federates.

6.2.6.3 Outputs

The service outputs a message containing the following information:

- Speed-made-good in m/s;
- Simulation time; and
- (Optional) model information.

6.2.6.4 Data/Formats Used

For the formats used for retrieving terrain data see the section about the Terrain Service.

A possible implementation of the output message with the trafficability information is an XML or JSON message over a REST API.

6.2.7 Notification Broker

6.2.7.1 Function

The function of the Notification Broker is to distribute notifications between the various services and federates in the simulation exercise. By introducing a notification broker as middleman, the consumers of the notifications do not have to be aware of the different producers of these notifications and no tight coupling between the components is created. This means that new modification services that produce notifications can be introduced to the federation without requiring changes to the consuming federates.

At start-up federates and services that are interested in receiving notifications will subscribe themselves to the types of notifications they are interested in. During the simulation, services that produce notifications will provide new notifications to the Notification Broker to be distributed. When providing the notification message, the producer will indicate which type the notification is, so that the Notification Broker can distribute it only to the interested receivers.

The need to distribute notifications in a distributed simulation is not specific to DSE only, therefore this notification broker is not specific to DSE either. One general notification broker could be used for all MSaaS components that are involved in the exercise.

6.2.7.2 Inputs

- Notification messages from services that have modified the environment.

6.2.7.3 Outputs

- Notification messages are forwarded to all federates and services that have subscribed to them.

6.2.7.4 Data and Formats

The notification message should contain at least the following fields:

- Time when the change occurred;
- Geographical area affected by the change, e.g., the bounding rectangle of the area;
- Layer of the environment that was modified, e.g., imagery, elevation or building vectors; and
- Producer ID, to prevent responding to own notifications.

Notifications should be exchanged between any simulation service or federate. As some components are not part of the HLA federation, e.g., a terrain modification service that works with the raster data provided by the terrain and weather services has no need to be part of the HLA federation, it is recommended that the Notification Broker offers both an HLA interface and a non-HLA interface. This also means that the notification broker should act as a gateway between those different interfaces and make sure any notification is distributed on both interfaces.

For the non-HLA interface, the TG recommends using web technologies as these are common nowadays and therefore easy to implement. For example, distributing a JSON message could be an implementation of the non-HLA interface.

6.3 CORRELATION APPROACH

One of the main requirements when introducing dynamic changes to the synthetic environment is that all participants of the distributed simulation exercise are affected equally and consistently by these changes. In other words, it should not be the case that fair-fight issues occur because some participants are not affected by the dynamic changes, while others are. In that case it could lower the usability and value of the simulation exercise. Therefore, the DSE architecture that MSG-156 defined tries to ensure that the dynamic changes to the synthetic environment are correlated for all participants. The following factors in the design of the architecture contribute to the correlation:

- Terrain and weather data is provided to all participants from common services. This prevents correlation issues that occur when (slightly) different source data is used for the terrain and the weather.
- Modifications to the terrain data are made by common services. This prevents correlation issues that occur because federates calculate the dynamic changes to the terrain differently. For example, if each federate must calculate craters in the terrain by itself, they could use different algorithms which result in differently shaped craters.
- The effect of the terrain conditions on the trafficability of vehicles is calculated by a common service. By performing the trafficability calculations centrally and using the same model, correlation issues that occur when federates calculate the trafficability in a different manner are prevented.

Although the aspects described above make it more feasible to ensure correlation between the participants, there are still some factors that could result in correlation issues and lead to fair-fight issues. One of these is that technical capabilities of the simulation systems will affect how they can represent the environment. For example, an infantry simulator will be capable to show more detail in the terrain than a flight simulator. So, although they both retrieve their terrain data from the Terrain Service, correlation issues can still occur due to their technical capabilities. Related to this, it could also be that not all simulations systems are technically capable to show dynamic changes in the environment, especially when legacy systems are included in the federation. Such systems might for example use a terrain that was created offline based on the data in the Terrain Service but lack the technical capabilities to update the terrain representation dynamically during simulation execution.

These remaining correlation challenges should be addressed in the process of setting up the simulation exercise. For example, the DSEEP process, which describes an engineering and execution process for distributed simulation exercises [1], contains pointers for addressing such questions. When such correlation challenges are addressed while selecting the federates that will participate or when designing the scenario, it will be possible to minimize fair-fight issues and get the maximum value out of the distributed simulation exercise.

6.4 REFERENCES

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Chapter 7 – DEMONSTRATION

To get hands on experience with the architecture to achieve a DSE, as presented in Chapter 6, the MSG-156 performed a concept demonstration of the architecture [1]. Various simulation systems and services from the participating countries were connected in a distributed simulation. And a scenario was executed that included interactions with a dynamic environment, based on the use cases identified in Chapter 3. This chapter describes the details of how this concept demonstration was setup and which lessons were learned from it.

7.1 USE CASE AND SCENARIO

A convoy consisting of one armored vehicle and four supply trucks is heading for a Forward Operating Base (FOB) to resupply the troops with necessary resupplies south of Alvdal (Figure 7-1). Intelligence reports states that all troops must avoid using the roads and bridges following the river Glomma, due to recent IED incidents and other insurgent activities. Furthermore, there have been reports of increased insurgent activity in the areas of Berset and Unset to the south. The convoy is planned along the roads east of the mountain Tron, through the valley of Tylldalen, crossing the mountain to the west in the vicinity of Tylldal. The crossing of the mountain involves traversing difficult mountainous roads. The convoy will have an F-16 in stand-by for support if needed.

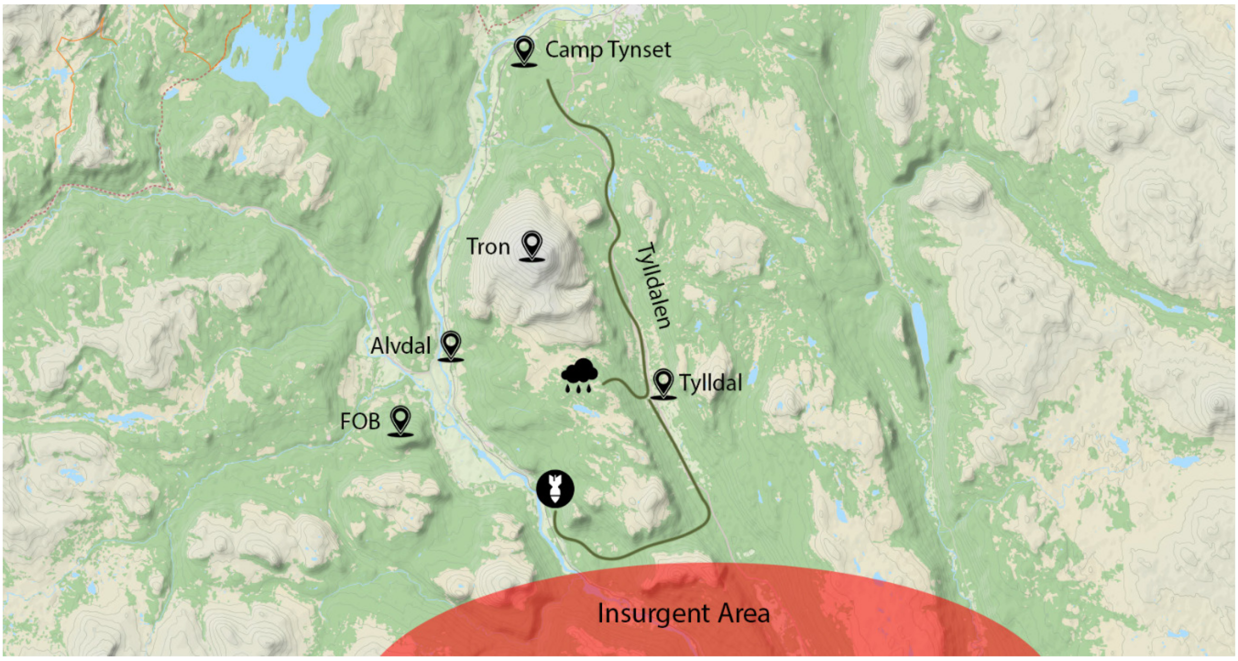

Figure 7-1: The Layout of the Demonstration Scenario.

The convoy leaves early morning from Camp Tynset towards Tylldal. During the morning hours, the fair weather quickly deteriorates into heavy rain showers. Since most of the mountain roads are unpaved and not well maintained, these dirt roads accumulate moisture and become slippery. When the convoy starts traversing the mountain road, the weather changes from rain to snow. The convoy is forced to a halt due to slippery roads and decreased visibility. The convoy lead decides to find a new mountain road further south, where the roads are more solid. Since this is closer to the insurgent areas in the south, the convoy tasks the nearby F-16 to provide route clearance and Close Air Support (CAS).

While the convoy moves further south, an insurgent group from Bergset establish a chain of IEDs supported by an ambush at Kvebergsmoen, south of Alvdal. The group is not spotted by the F-16 due to weather and thick cloud coverage, degrading the visibility and sensor performance of the pilot and aircraft. When the convoy clears the southern mountain pass, one of the convoy trucks hit the IED and is damaged beyond repair. The convoy halts in the area. A short while after, the convoy receives incoming mortar fire from the insurgent group ambush from a compound situated in the hills nearby. The weather has cleared, so the F-16 uses the IR sensors to quickly determine the origin of the mortar fire and engages the insurgents. The F-16 manages to engage the insurgents with a precision guided bomb, destroying the compound and disabling the insurgents. The convoy manages to call for Quick Reaction Force (QRF) and medical evacuation (MEDEVAC) while the F-16 provides cover.

7.2 PARTICIPATING FEDERATES AND SERVICES

In this section the federates and services that were integrated for the concept demonstration are discussed. The different components will be described and how they have been integrated into the architecture for dynamic environments is also discussed.

7.2.1 Vehicle Simulator

The vehicle simulator was provided by Guardiaris from Slovenia. The simulation software is developed by Guardiaris and is used in number of simulators produced by Guardiaris. In this case the code of the IFV crew training simulator was used. To ease integration and testing required in the demonstration a desktop version of the simulator was used. Since the software is Guardiaris proprietary technology it was possible to make modifications and improvements to it where required, especially to use new interfaces and protocols as they were defined by the solution architecture.

The simulation and image generation software simulate vehicle behavior, dynamic terrain and weather changes and displayed all other entities participating in the demonstration scenario. Figure 7-2 shows the screenshot taken from the vehicle simulator with visible artillery shell impacts on the road.

Figure 7-2: Artillery Shell Impacting on Road in Vehicle Simulator.

7.2.1.1 Terrain

In the vehicle simulator the terrain data is received by request from the terrain service. Terrain rendering is implemented via a virtual texture-based material renderer, which takes elevation and color data as input and converts it to a height and material maps. Vector areas such as forests and roads are then rendered into the material map and foliage and vegetation is procedurally seeded in run-time. Roads also flatten the ground where they are placed, and they apply a special road material and add a high-resolution road decal.

Run-time terrain modifications are possible either via re-downloading elevation data or by using a run-time terrain modification system which uses vectors with depth and width to cut into the terrain and can also change the material and apply a decal.

Once the notification for changes to the elevation data arrives a request for the updated terrain data is made to the terrain service. After new data is applied to the terrain representation, artillery shell crater visualization is added to the same detonation position as received via HLA.

Figure 7-3 shows the terrain used in demo. Screenshot is taken from the vehicle simulator simulation software.

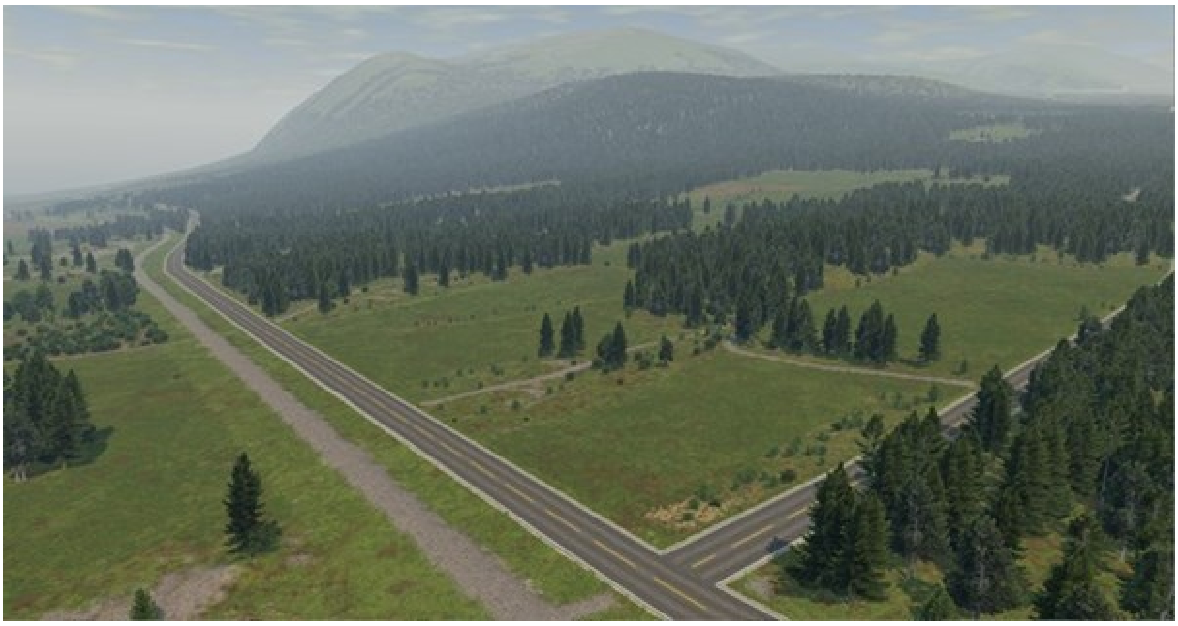

Figure 7-3: Terrain Used for Demonstration in Vehicle Simulator.

7.2.1.2 Weather

In the vehicle simulation the weather data is received via the HLA METOC protocol. Initial data is distributed to the vehicle simulator after it has successfully connected to the federation. Afterwards the weather data is received by periodic requests via the HLA protocol. The vehicle simulator is requesting precipitation data and cloud cover data, specifically. All the received data is appropriately applied to the synthetic environment as represented in the simulation. Weather and general environment is rendered via a Rayleigh scattering renderer which realistically portraits the basic clear sky and time of day. On top of that clouds, volumetric fog and precipitation effects are rendered to get a realistic feel of the environment setting. Snow on the terrain is dynamically and procedurally applied based on snow settings, depths up to 30 cm are currently visually acceptable.

Figure 7-4 shows snow precipitation and snow layer on the ground as rendered in the vehicle simulator.

Figure 7-4: Precipitation and Snow in the Vehicle Simulator.

7.2.1.3 Trafficability

The trafficability data is applied to the vehicle simulator as well. Therefore, an implementation of data requests to the trafficability service had to be implemented. Received data is in real time applied to the driving capabilities of the vehicle. It was decided that a two-second refresh rate of the trafficability data is sufficient for a realistic trafficability in the simulator.

7.2.2 Flight Simulator

The flight simulator in the demonstration was provided by Royal NLR in the Netherlands. The simulator is a research simulator of a fighter aircraft, which includes a simulation of a targeting pod. This allowed the simulator to provide the close air support role in the demonstration scenario. Figure 7-5 shows the full simulator; for the demonstration, the simulator software was used in a desktop setup to ease testing and integration. As it is a research simulator it was possible to make code modifications to use the new interfaces defined in the solution architecture. Sections 7.2.2.1 and 7.2.2.2 discuss how the terrain and the weather data was used in the fighter simulator.

7.2.2.1 Terrain

The image generator used in the flight simulator does not support consuming data from OGC interfaces directly, so it was not possible to connect the simulator directly to the terrain service. The traditional approach would be to download the terrain data from the terrain service and then process it with the Database Generation System (DBGS) of the flight simulator to create the CDB database that the image generator needs. But for the demonstration an intermediate approach was developed. A prototype conversion tool was made that queries the OGC interfaces of the terrain server and saves the data in the CDB file structure. Figure 7-6 gives a graphical representation of this process. Especially for the imagery and elevation layers of the terrain data this is a relatively straight forward conversion. The advantage is that the data does not have to be downloaded and that the processing is quicker. Also, when new data is available in the terrain service the conversion tool can just be run again.

To support dynamic changes to the terrain the idea was to run the conversion tool again for the area affected by the dynamic change. This would be possible using the information in the notifications that are provided. But since the image generator provides no way to notify it that the CDB content has been modified due to the dynamic changes, this approach was not further tested in the demonstration. The flight simulator therefore only used the static terrain based on the data in the terrain service and did not visualize the dynamic changes to the terrain.

Figure 7-5: Research Flight Simulator from Royal NLR.

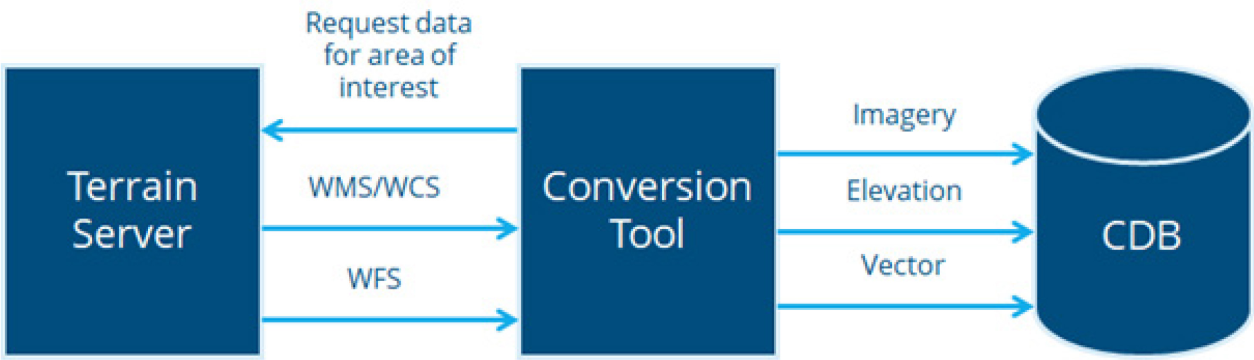

Figure 7-6: Conversion Tool to Generate CDB from Terrain Server Data.

For toggling the damage state of the buildings an intermediate solution was used as well, as the image generator cannot read the buildings directly from the terrain service and does also not support changing the damage state based on attributes provided by the terrain service. An intermediate tool was made that reads the building placement information from the terrain service. In the attributes of this vector data the function state (normal or destroyed) is stored as well. The intermediate tool then injects these buildings into the simulator as entities. When a notification is received that the building vector layer has been updated, the tool will download the data from the terrain service and update the entity representation in the simulator. This will result in the image generator switching between the normal and destroyed state. Since the number of buildings that could be damaged in the demonstration was limited, this approach worked.

The approaches described here to work with the terrain service are an example of how legacy systems that do not support the OGC interfaces directly can still work with the terrain service data. This way, one can still benefit from using a common terrain service, like data versioning and updates or to have a consistent damage representation.

7.2.2.2 Weather

The image generator of the flight simulator already supported the visualization of various weather effects, including precipitation, cloud layers and individual clouds. The image generator uses a CIGI interface for the simulation to drive this visualization. Within the demonstration this existing functionality was used, but with an additional interface to request the weather data from the weather server using the HLA METOC FOM. For this, a process was added that regularly requests the weather data at the location of the fighter aircraft and the responses from the weather server were translated to the existing weather representation in the simulation. Besides the request at the location of the aircraft, used for the flight dynamics, three additional requests were made to get the average weather in a circle around the aircraft; this data was used to drive the out-of-the-window visualization which covers a larger area. The visualization supports three separate cloud layers, so each of the three requests corresponded with the altitude of one of these cloud layers.se fills one of the cloud layers. The data models used in the METOC FOM and the CIGI interface are quite similar, therefore the mapping between them was straightforward.

The image generator supports cloud layers and individual cloud objects. As the weather server does not provide the last, the cloud layer information was used. This means that the base altitude, ceiling altitude, coverage and type of clouds are shared, but it is up to the simulator to decide on how to represent this. This approach makes it hard to have a good correlation when it comes to gaps in the cloud layer. As an alternative it was considered to request a cloud coverage raster from the weather server and use that as basis for the visualization of the clouds but injecting such a raster image was not supported by the image generator.

The weather data was not only used for visualization by the image generator, but it was also provided to the flight dynamics model. This meant that the atmospheric conditions and wind as provided by the weather service were used to determine the dynamics of the aircraft.

7.2.3 Computer-Generated Forces

To represent the convoy and the opposing forces, the group used VR-Forces (version 4.7) [2] as the Computer Generator Forces (CGF) tool for the demonstration. VR-Forces is a CGF platform developed by MAK Technologies. In the demonstration, VR-Forces were mainly used as the CGF, but it also played a role as the demonstration stealth viewer. This enabled the group to visualize the scenario, during development, planning and execution (Figure 7-7).

As stated in the scenario, the convoy would halt when traversing a mountain road due to wind, deteriorated soil conditions and snow. A plugin was developed for VR-Forces that queries the Trafficability Service (see Section 7.2.6) for each ground vehicle entity managed by the VR-Forces simulation engine at 2 Hz.

The obtained maximum speed (or *speed-made-good*) was used to limit the vehicle's current speed where necessary. A small GUI extension can be used to optionally define convoy properties as part of the scenario definition, so that the trafficability model can take the position a vehicle within the convoy into account (vehicles further up the convoy typically have a lower trafficability due to track forming in muddy roads) (Figure 7-8).

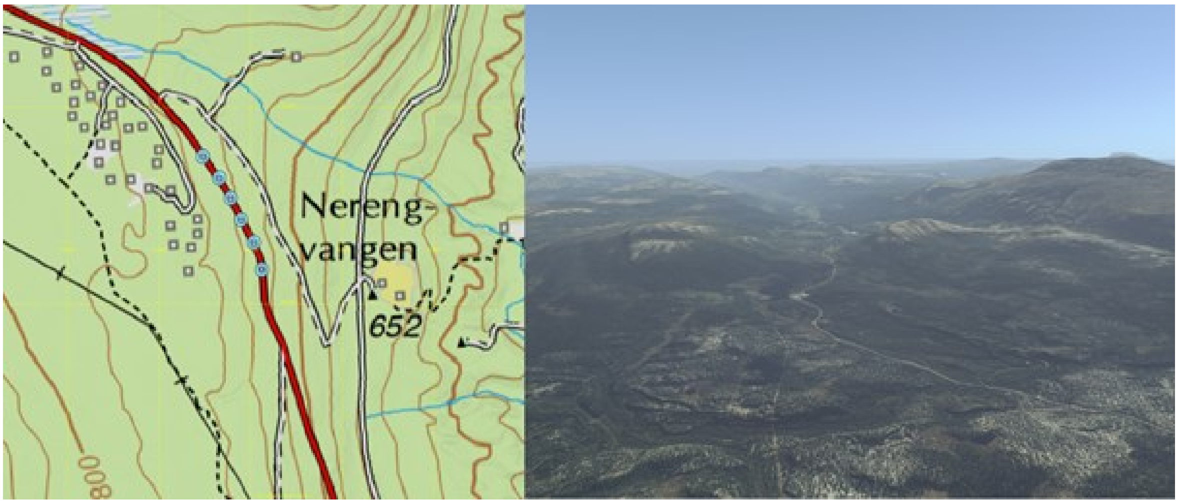

Figure 7-7: The VR-Forces Plan View (Left) and Stealth View (Right).

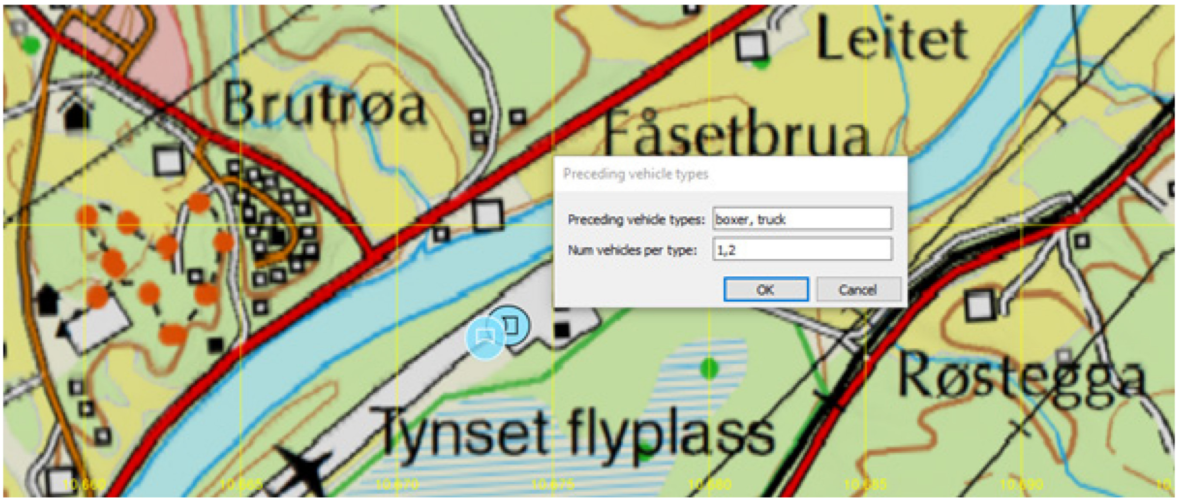

Figure 7-8: The VRF Plugin GUI.

The version of VR-Forces used in the demonstration included support for some of the OGC standards to import terrain data from the Terrain Service, however the TG could not get this to work properly. Problems encountered where differences in versions of the WCS standard supported by VR-Forces and the Terrain Service, and the lack of support of HTTPS communication. This shows that even though various tools support the same standards, there are still issues that can be encountered when connecting them. In the end the TG used a static environment representation in VR-Forces, as having a dynamic representation in the CGF did not have priority for the scenario. For instance, VR-Forces did not need to know about the weather data directly, as the effect of the weather on the entities was the responsibility of the Trafficability Service and obtained through the plugin.

7.2.4 Terrain Service

The German SES implementation of the Terrain Service was used in the demonstration. This implementation consists of several standardized OGC-Services, namely:

1) A Web Map Service,
2) A Web Coverage Service including the transactional extension for the dynamic component, and
3) A Web Feature Service.

The services and the complete terrain dataset were deployed on an externally available webserver and secured by TLS and HTTP-Authentication. As a result, the Terrain Service was available all the time to all group members for development, testing, and the final demonstration.

7.2.5 Weather Service

In order to evaluate a service-based architecture for correlated dynamic weather effects within a synthetic environment, a source of weather data was required to support weather and atmospheric 1st and 2nd order effects models operating within the synthetic environment. A suitable candidate weather service was not available for the demonstration and so, following the MSaaS architecture of the TG, the UK developed a Weather Service to provide a centralized source of weather information. The Weather Service consumes a real-world set of weather data and uses this along with the International Standard Atmosphere (ISA) model to provide a common source of weather and atmospheric data.

7.2.5.1 Weather Data

Weather data is supplied to the server in the form of a NetCDF format gridded weather dataset containing the following weather dimensions:

1) Cloud Coverage: Cloud coverage layers describing the density of the low, medium and high cloud;
2) Cloud Base Height: Raster coverage layer detailing the cloud base height in meters;
3) Precipitation: Total precipitation coverage map detailing the total amount of precipitation that has fallen in an area;
4) Snowfall: Snowfall precipitation coverage map detailing the amount of snow that has fallen in an area;
5) Surface Pressure: Surface pressure layer;
6) Wind U: Wind U component;
7) Wind V: Wind V component; and
8) Surface Temp: Surface temperature coverage map.

7.2.5.2 Weather Service Model

The NETN METOC HLA FOM data model uses a number of atmospheric data parameters that may not be provided in a weather dataset’s data model, or maybe provided in different units. For example, the NETN METOC FOM provides air pressure information which was not present within the weather dataset used in the demonstration.

Where the weather data may not provide parameters required by the NETN METOC FOM, the weather server uses the International Standard Atmosphere (ISA) model to derive the missing parameters.

The Weather Service's WCS interface supports requests that include grid offsets for resampling of the weather data allowing a client to request an area of weather data at a higher resolution than the source data. This is useful as weather data may only be available at resolutions too low to be used natively by simulation models. To support these requests, the weather service model uses bicubic interpolation to resample the weather data to the resolution requested by the WCS client. This approach was sufficient for the purposes of the group's demonstration but could be enhanced to provide more advanced refinement for example through the use of a more advanced resampling model or even a full weather model (depending on the processing power and time available).

While spatial refinement can be achieved relatively simply, it is thought that temporal refinement would have introduced a lot of challenges especially for data such as cloud coverage where the data was used for visualization purposes. The source dataset provides hourly intervals of gridded cloud coverage data and to interpolate between the hourly data would require a model capable of consuming cloud formations for an area and progress them though an hour resulting with formations that match the next hour of source data. This is likely to require a complex weather model and, due to runtime constraints such as compute resources and the need for timely processing of client requests, may only be solved by increasing the temporal resolution of the source data.

7.2.5.3 Weather Service Interfaces

The Weather Service provides data on two runtime interfaces:

- **NETN METOC HLA:** An HLA interface that populates the NETN METOC HLA FOM interface allowing federates to subscribe to, and request, weather, and atmospheric parameters.
- **Web Coverage Service (WCS):** A raster interface accessible through a secure HTTPS web interface and allowing simulation systems to request and retrieve gridded weather data.

The primary interface to the Weather Service is via an HLA interface that populates the NETN METOC HLA FOM. This interface allows federates to subscribe to, and request, weather, and atmospheric parameters for four aspects of a synthetic environment:

1) Atmospheric Layer: Data pertaining to the state of the weather for a layer of the atmosphere including wind speed and direction, precipitation type and rate, humidity, temperature and visibility, and cloud type and coverage density.
2) Land Surface: Data pertaining to the state of the weather at ground level including wind speed and direction, precipitation type and rate, humidity, temperature and visibility, and snow depth, surface moisture, and road ice conditions.
3) Water Surface: Data pertaining to the state of the weather and the surface of a body of water including wind speed and direction, precipitation type and rate, humidity, temperature and visibility, and ice thickness and coverage, wave height and length, and current speed and direction; and
4) Water Layer: Data pertaining to the state of a layer of a body of water including temperature, salinity, and current speed and direction.

The federates operating in the demonstration system only used the Atmospheric and Land Surface aspects of the data provided by the service. However, this is due to the nature of the models within the federates, and the Water Surface and Layer information is important to include in such as service for example in order to support simulation components operating maritime focused models.

It is expected that in an MSaaS environment there will be components that require weather data but would not be HLA federates. One example of this is the Soil Conditions Service that requires gridded precipitation data to allow it to model the impact of rainfall on the soil conditions, which affects the mobility and trafficability of land entities traversing the terrain. As a service, there is no requirement for the Soil Conditions Service to join the simulation's HLA federation and as such a separate interface is required on the weather service to support non-HLA systems. In the case of the group's demonstration system, the Soil Conditions Service was the only non-HLA system requiring weather data, and it required gridded precipitation data. Due to the gridded nature of the required data, it was decided that a Web Coverage Service (WCS) web interface would be added to the METOC Weather Server, through which, gridded coverage maps (such as rainfall coverage) could be discovered and requested.

7.2.5.4 Weather Time

It was recognized that there was a need for the weather to progress during the simulation run allowing the effects of changing weather to be observed within the synthetic environment. The Weather Service has a time model that maintains a measure of the amount of weather time that has elapsed within the synthetic environment. This allows the weather server to progress the weather during the simulation such that the weather data supplied through the HLA interface changes over time. The time model also allows the real weather data time to be mapped to a simulation start time (so that an interesting hour of weather data can be equated to a different time within the simulation system), and offers an ability to run the weather data in faster than real time providing:

- **Rapid Weather Changes:** The ability to view a wider range of changing weather conditions within the simulation environment in a shorter time period; and
- **Greater Weather Effect:** The ability to achieve a weather effect (or second order effect) within the simulation environment in a shorter time period.

The Weather Service's WCS interface supports time parameters allowing clients to request weather data not only for a specific area, but also for a specific time. For this reason, the WCS interface does not provide data based on the Weather service's time model, but instead relies on WCS web clients to maintain a model of the data time that they require and request data with a WCS time parameter.

The NetCDF weather dataset provided used by the group contained data for the 3rd December 2019 stored in hourly intervals and the time-based nature of the weather data allowed the weather server to progress the weather during the group's experimentation and respond to WCS time-based requests.

7.2.6 Soil Conditions Service

The Soil Conditions Service, provided by TNO, runs a simulation model of the effect of precipitation on the soil. It obtains the dynamic weather state at a fixed interval and periodically outputs the modified soil state to the terrain server. This soil state becomes a (dynamic) input for the trafficability service, which is subscribed to updates to the soil moisture layer. The Soil Conditions Service can process a given area of interest in real time, running its model at 2.5 Hz. For scalability, the service runs the model in parallel on tiles of 1 x 1 km. These parallel models communicate at tile borders to support continuous flow of surface and soil water.

The Soil Conditions Service runs a dynamic simulation model to update the soil moisture layer, which is detailed in Annex B. In short, each simulation iteration, the model computes per simulation grid cell the rainfall absorption into the soil, its evaporation and water spill to neighboring cells (using local elevation and water puddle level differences and gravity), given the most recent precipitation grid information obtained from the weather server, the surface types of the terrain, and the previous state of the model. The advantage of using this model over a simple soil saturation accumulation model is that water puddles and muddy surfaces form where one would expect, given the elevation model and the distribution of surface types.

7.2.7 Trafficability Service

The Trafficability Service is a co-creation of TNO and the Dutch MOD, built as a .NET ASP Webservice. Its purpose is to provide a maximum attainable speed for a specific vehicle type at a specific location. Simulators can request the maximum speed or *speed-made-good* by supplying the API with:

- Current position coordinates;
- Current heading;
- Type of vehicle, and in case of a convoy of vehicles; and
- All preceding vehicle types and number of preceding vehicles per type.

Doing so will return a JSON response to the requestor with the speed-made-good, as seen below:

JSON Response:


```
{
 "data":                                                        {
 "speedMadeGood":                                               {
 "speedInMS":                                                   0
 },
 "simulationTime":                      "2020-11-16T12:37:09.282Z",
 "messages":                                                    [
 "string"
 ]
 }
}
```


7.2.7.1 Trafficability Model

Internally, the Trafficability Service uses a trafficability model to compute the speed-made-good. The model used in the experiment is a custom implementation of the old Vehicle Cone Index trafficability models detailed in, amongst others, Ref. [3]. Annex C describes the implementation of the model and the trade-offs and design choices in more detail.

7.2.7.2 Implementation Challenges

It is important for the Trafficability Service to remain responsive to be able to supply query results in a timely manner. Simulators traversing the terrain need the maximum speed they can travel almost instantly. Potentially there can be a lot of simulators querying the Trafficability Service at the same time, putting a high load on the Trafficability Service. On top of that the Trafficability service also needs to be 'a good citizen' in the federation and not put too much load on the other services providing it with data requests. The related services supply the Trafficability Service with data stored in GeoTIFFs. Creating those GeoTIFFs takes processing time and they can become quite large adding to the network load and transfer time. In order for the Trafficability Service to remain responsive and return data in a timely manner, those challenges needed to be solved.

In summary, the Trafficability Service needs to be able to:

- Handle many simultaneous requests;
- Respond to those requests as quickly as possible; and
- To play nice with the other services by not putting them under heavy load.

7.2.7.2.1 Request Handling

The Trafficability Service is built as a C# ASP .NET API. This architecture is relatively lightweight and fast in itself, but to further improve performance, containerization was employed to make the service scalable. This way, it would have been possible to scale up the number of services handling speed requests quite easily. A side benefit of using a container is the ability to deploy it on other systems without much configuration, because the container is a self-contained unit. Replicating the service is further simplified by its design as a stateless query service: all relevant information is passed in the request (e.g., preceding vehicles in a convoy), therefore, the service does not need to maintain and share any results from previous requests (e.g., tracks generated by vehicles).

Scaling out the containers to multiple instances has not been employed during this demonstration. The single service was more than able to handle the number of requests that it was receiving during this demonstration.

7.2.7.2.2 Responding Quickly to Requests

The bottleneck of responding quickly to requests is the time it takes for the Terrain Server to create the required input GeoTIFFs and transport them across the network. So, a strategy of pre-fetching had to be employed. The Trafficability Service can be setup to pre-fetch information for starting locations of vehicles ahead of time. Also, it fetches a larger area of data instead of just one coordinate at a time; the size of the requested tiles was empirically determined. This information is cached so multiple requests in the same general area would not lead to querying the supplying services again, saving precious time.

7.2.7.2.3 Reducing Load on Other Services

The load on services that provide data to the Trafficability Service is already mitigated by caching all requested information. However, in a DSE, cached tiles can quickly become outdated, and the service needs to know when to update its cached tiles. For this, the discussed notification system was employed: the services modifying the data are tasked to send out a notification when their data changes. Since the Trafficability Service is implemented as a stateless HTTP service, it has a supporting component called the NotificationForwarder, which subscribes itself to the notification broker, and upon receiving notifications forwards the information to the Trafficability Service, causing the service to refresh stale information in the cache. Further improvements could be made to reduce the load on other services, for instance only refresh recently used cached data and discard older data instead.

7.2.8 Terrain Deformation Services

In support of the UK "SCORE" project, a prototype Terrain Deformation Service was developed that employed a number of deformation services, each of which updates an aspect of a terrain dataset to reflect events occurring within a synthetic environment. Each deformation service specializes in one dimension of the terrain dataset (i.e., elevation or imagery, etc.) and monitors the federation for events (such as a detonation) that might affect that data dimension. On such an event, the relevant deformation service retrieves terrain data areas affected by the event from the terrain service. This data is then modified (according to the deforming event) and stored back in the terrain server to be consumed by simulation models. This approach ensures that all simulation models operating within the wider simulation system operate with the same representation of the terrain and removes the need for models to operate their own often un-correlated deformation models.

The deformation services developed were identified to provide the Federate-Terrain Interaction Services capability within the group's demonstration system.

7.2.8.1 Terrain Deformation Model

The deformation micro-services deform terrain through the use of a simplistic deformation model based on a pre-canned impact crater model. This model consists of:

- Crater Image: A greyscale image of a munition detonation crater that can be blended onto existing terrain imagery to add the image of a crater to the imagery; and
- Crater Profile: A 3-dimensional profile of a munition detonation crater that can be applied to existing terrain elevation data to deform the terrain elevation 3D mesh.

On receipt of a detonation event, the deformation micro-services apply the model to the terrain imagery and elevation data through the following steps:

- The micro-services receive a detonation event from the HLA federation;
- The size of the detonation crater is calculated from the detonation event's warhead and detonation result, this is achieved by means of a look-up table;
- Terrain data (imagery and elevation) for an area that bounds the crater is retrieved from the terrain server;
- The crater model is scaled to the size determined in step 2;
- The crater model is blended with the terrain imagery to create the effect of a crater that still contains some existing terrain imagery features;
- The crater model is added to the terrain elevation by subtracting the cater 3D model from the original elevation data;
- The new terrain imagery and elevation data is uploaded to the terrain server as a replacement section of the terrain database.

The deformation model allows varying sizes of crater to be applied according to the detonating munition type, however it is a very simplistic model that was designed to facilitate experimental activities to investigate the correlation of dynamic terrain effects. A production system would likely use a more complex that might allow for more accurate crater modelling based on factors such as:

- Munition and warhead type;
- Detonation location, for example above the terrain, on impact with the terrain, or below the terrain;
- Material type of the affected terrain, for example soil, concrete, asphalt, etc.; or
- Environmental state of the affected terrain, for example frozen ground, high content of water, etc.

Figure 7-9 shows a before and after image of an area of the terrain database deformed by the deformation service.

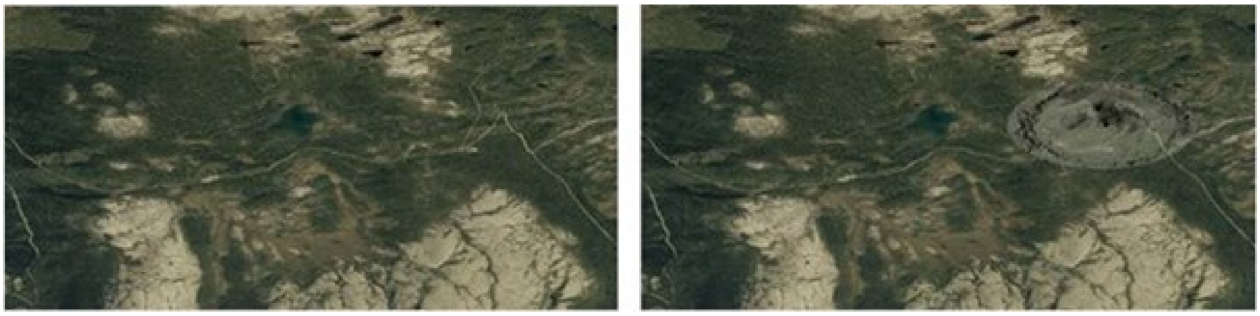

Figure 7-9: Example of Terrain Deformations.

7.2.8.2 Terrain Deformation Interfaces

The terrain deformation services use three interfaces:

1) **WCS and WMS Terrain Retrieval:** Web Coverage Service (WCS) and Web Mapping Service (WMS) interfaces used to request and retrieve subsets of terrain elevation and terrain Digital Orthophoto (DOP) imagery data from the terrain server;
2) **WCS Terrain Upload:** WCS interface for uploading georeferenced subsets of terrain elevation and imagery data to the terrain server; and
3) **Notification:** interface for notification of terrain update to federates and other services via the Notification Broker.

7.2.8.2.1 Terrain Retrieval

The deformation services were developed to operate on a CDB database. In order to interface the services to the terrain server provided for the group's demonstration, a translation layer was developed that allowed CDB-based requests to be made by the deformation services. These requests were then used to construct WCS web requests that retrieve terrain sections that have the correct pixel spacing and geographic bounds to be CDB compliant data tiles. This is illustrated in Figure 7-10.

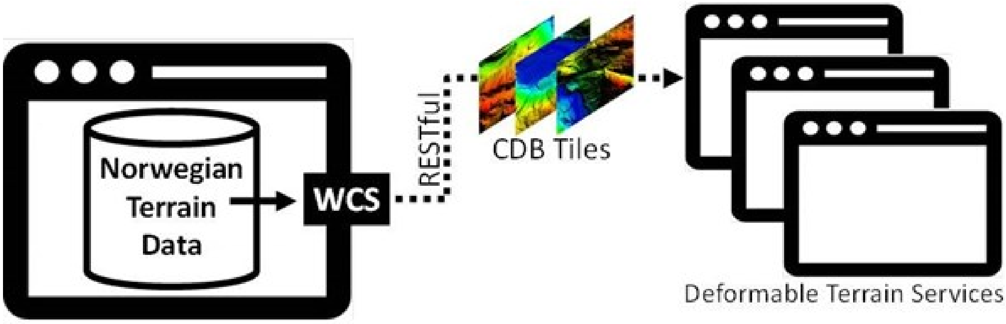

Figure 7-10: Terrain Deformation Workflow.

Figure 7-11 shows a section of the terrain database (the elevation data layer) used by the group. The three images at the bottom of the illustration show the CDB tiles retrieved through the translation layer by the deformable terrain services.

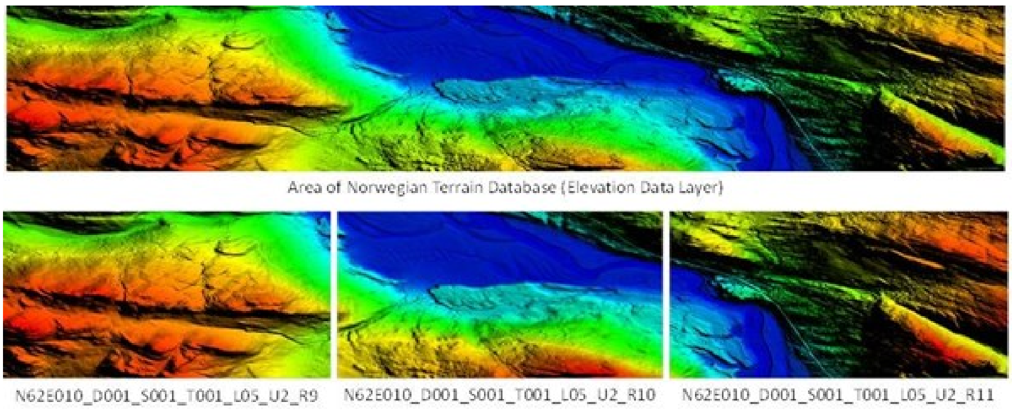

Figure 7-11: Example of Deformation Service Processing Data in Tiles.

7.2.8.2.2 Terrain Upload

In order to allow the SCORE deformation services to update the terrain server; a terrain upload interface was added that allowed the services to post modified sections of terrain data to the server. This interface took the form of a WCS mechanism that accepted a compressed terrain update package containing:

1) A TIFF file containing the updated section of terrain data; and
2) A world file detailing the pixel spacing and geographic boundaries of the terrain update.

7.2.8.2.3 Notification

Following an update to the terrain server, a JSON message is posted to the Notification Broker to inform simulation systems that an aspect of the terrain data has changed. This JSON message is posted through a ZeroMQ-based Notification Broker, see Section 7.2.9 for more details.

7.2.9 Building Damage Service

An important requirement of a dynamic terrain representation is achieving correlation of effects not only across federates operating within the synthetic environment modelled by the dynamic terrain, but also across the individual data dimensions within the dynamic terrain representation. For example, a munition detonating a synthetic environment should not only cause terrain elevation and imagery data to be deformed, but also aspects of the terrain such as any infrastructure, roads, buildings, and vegetation within the detonation area.

For the MSG-156 demonstration, building information was stored within the group's terrain server as an attributed set of point features. In keeping with the group's MSaaS architecture, a Building Deformation Service provided single centralized model of the impact of munitions on buildings within a synthetic environment.

7.2.9.1 Building Damage Model

The Building Deformation Service monitors a synthetic environment for detonation events, and uses a simplistic model of how the detonations affect building status in which a building's state simply switches from undamaged to destroyed based on distance from the detonation event by employing the following steps:

- Iterating through the building point features in the terrain server;
- Determining which buildings are within a 30 meter radius of the detonation location;
- Constructing for each building within the affected radius an update to indicate that the building's status is now destroyed; and
- Issuing the updates to the terrain server.

Whilst the model used by the Building Deformation Service is simplistic, it allows the concept of a centralized common deformation service to be exercised within an experimental system and allows the service to provide a correlated view of damaged building states across all federates within the system. It is likely that for a production system, such a service would model building damage based on data such as:

1) Detonating munition type, warhead composition, and detonation result;
2) Building size, construction, and material;
3) Orientation and location of the detonation to building, including modelling levels of damage to the building; and
4) The terrain and other features surrounding and/or between the detonation and building.

As with most models however, increasing levels of complexity requires increasing compute resources to operate the model. However, the MSaaS service-based approach taken by the MSG-156 services provides an opportunity to leverage the computing and data capacity resources offered by cloud-based infrastructures (see, for example, Ref. [4]).

7.2.9.2 Building Damage Service Interfaces

The service relies on three runtime interfaces:

1) HLA Interface using the Realtime Platform Reference (RPR) FOM;
2) Web Feature Service (WFS) transactional web client interface; and
3) ZeroMQ-JSON notification interface.

7.2.9.2.1 HLA Interface

The service is an HLA federate that subscribes to detonation event information from an HLA federation. This allows the service to receive timely notification of detonation events but does require that the service be able to connect to an HLA RTI. For a service that might potentially be deployed on an MSaaS supporting infrastructure (such as a remotely hosting cloud platform), the choice of including a HLA interface may require that a HLA federation be extended outside of a local simulation system and across a WAN, for example by using HLA Boosters. This may not be a suitable solution for all simulation systems as it potentially exposes the whole HLA traffic to external systems and this may not be possible due to security considerations. An alternative could be to have a detonation-broker operating locally to the HLA federates that would transmit a minimal set of information to a remote instance of the service.

7.2.9.2.2 WFS Transactional Interface

Updates to building data stored within the terrain server are achieved through the use of the terrain server's WFS transactional interface. This interface allows attributes of the building vector data to be changed based on key-values pair unique IDS. In the event that the service determines that a building has been destroyed, the following update is issued to the terrain server causing its status to change from 'Operational' to 'Destroyed'.


```
<?xml version="1.0" encoding="UTF-8"?><wfs:Transaction
xmlns:tas="http://www.supportgis.de/transaction/simulation"
xmlns:gco="http://www.isotc211.org/2005/gco"
xmlns:gss="http://www.isotc211.org/2005/gss"
xmlns:gts="http://www.isotc211.org/2005/gts"
xmlns:gsr="http://www.isotc211.org/2005/gsr"
xmlns:gmd="http://www.isotc211.org/2005/gmd"
xmlns:xml="http://www.w3.org/XML/1998/namespace"
xmlns:gml="http://www.opengis.net/gml/3.2"
xmlns:xlink="http://www.w3.org/1999/xlink"
xmlns:sedris="http://www.supportgis.de/namespaces/sedris/1.0"
xmlns:xs="http://www.w3.org/2001/XMLSchema"
xmlns:dummy="http://www.supportgis.de/collection_to_import"
xmlns:wfs="http://www.opengis.net/wfs/2.0"
xmlns:fes="http://www.opengis.net/fes/2.0" service="WFS"
version="2.0.0"><wfs:Update
xmlns:sedris="http://www.supportgis.de/namespaces/sedris/1.0"
typeName="sedris:SE_Value"><wfs:Property><wfs:ValueReference
action="replace">sedris:string_value</wfs:ValueReference><wfs:Value>DESTROYED</w
fs:Value></wfs:Property><fes:Filter><fes:ResourceId rid="id1c7b88c1-acf6-4797-
b432-ae0c44c016ca"/></fes:Filter></wfs:Update></wfs:Transaction>
```

7.2.9.2.3 Zero-MQ-JSON Notification Interface

Following an update to the terrain server, a JSON message is posted to the Notification Broker to inform simulation systems that the building data has changed. In the event that multiple buildings are destroyed, the service issues a single notification after the last update to the Terrain Server has been actioned. This ensures that all updates are complete to allow subscribing systems to download a set of updates in a single request.

7.2.10 Notification Broker

In the DSE solution architecture it has been identified that the Notification Broker should have both an HLA and a web-based interface, so that both HLA federates and services that are not part of the HLA federation can send and receive notifications. However, for the demonstration the TG simplified this and decided to only implement one communication protocol. Since not all services in the demonstration are part of the HLA federation it was decided to only use a non-HLA technique. For this ZeroMQ was selected, because this library is relatively easy to implement, is available for many programming languages and does not require a server component to be installed and configured to work [5].

For the content of the notifications a JSON message was defined that includes information like the layer that has been modified and which geographical area is affected. Figure 7-12 shows an example of such a notification message send by the Terrain Deformation Service.


```
{
  "Notification": {
    "IssuerId": "FederateTerrainInteractionSrv",
    "Bounds": {
      "EPSG": 4326,
      "XMin": 10.5959787540503,
      "YMin": 62.0718513164736,
      "XMax": 10.8101740332975,
      "YMax": 62.1864000303942
    },
    "Layer": "ELEVATION",
    "Time": "2020-04-23T13:22:22.1311744+02:00"
  }
}
```


Figure 7-12: Example Notification Message.

The Notification Broker implementation could be based on a ZeroMQ sample, and it just forwards a notification to any federate or service that has subscribed to receive them. This was literally only a few lines of code to write.

Slovenia hosted this application, so that all other participants in the demonstration could subscribe to it to receive notifications or send their own notifications to the broker. The Notification Broker was setup on Guardiaris server, and all other participants were able to access it without any third-party VPN applications. To avoid any security issues each participant was assigned a specific port and IP. The chosen approach worked well.

7.3 TERRAIN DATA USED IN DEMONSTRATION

The scenario was situated in the Norwegian mountains in an area where NATO held the Trident Juncture 18 exercise (Figure 7-13). The terrain data used in the demonstration was a 40 x 40 km area south of Tynset in Norway. Most terrain data were provided by Norway and the Norwegian Mapping Authority, which has a large collection of publicly accessible terrain data available online [6]. Some elements had to be created or modified by the TG, so that it would fit the scenario. The following sections describe the source data that was used. More details about the terrain data required and data structures can be found in Chapter 4.

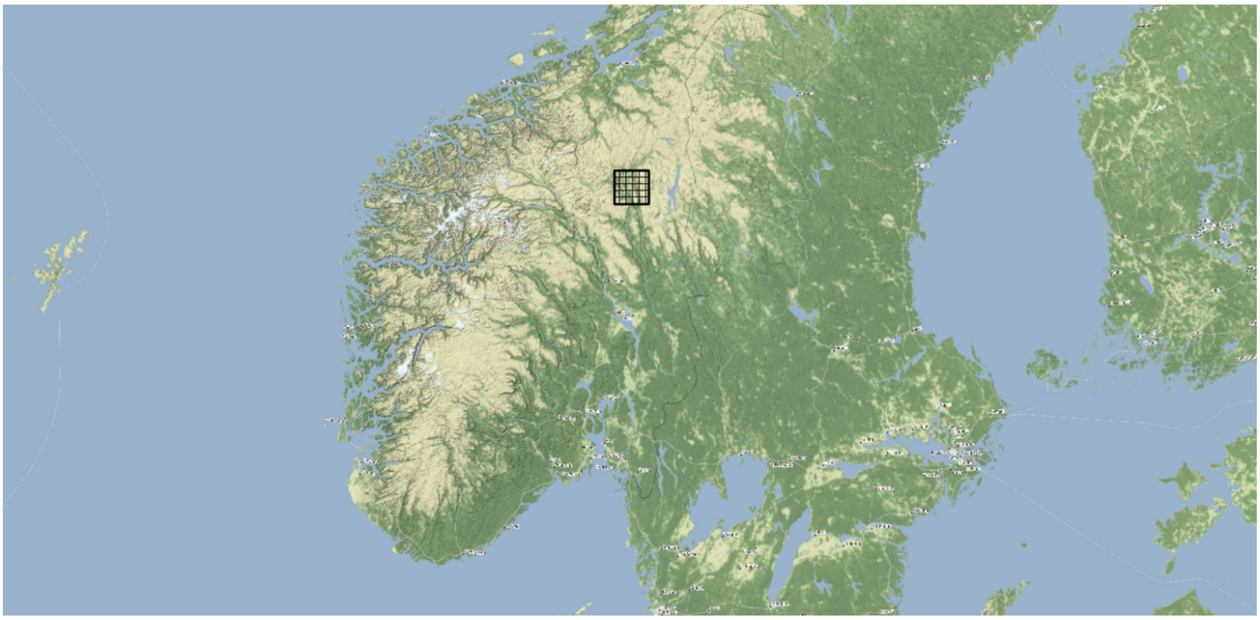

Figure 7-13: Geographical Area Used for the Concept Demonstration.

7.3.1 Aerial Imagery

High-resolution aerial imagery of the area is subject licensing, so an available lower-resolution aerial image was used. The source resolution was 5 m, re-rendered as several 1 m GeoTIFF images. The re-rendered images were also repainted to increase detail in certain areas, as well as altered to fit with elements from the scenario, for instance roads and paths over the mountain. It would have been beneficial to have artificially created aerial or satellite imagery. It is often troublesome to acquire license free high-resolution aerial or satellite imagery, especially when doing work between different nations.

7.3.2 Raster Map Data

A raster map was also included, to provide the ability to display a “paper map” in C2-systems. The map is part of the Norwegian “N50” data set and have a scale resolution of 1:50 0000. The image used in the demonstration was a GeoTIFF with a resolution of 2.5 m per pixel.

7.3.3 Elevation Data

The elevation data were sourced from a public access high detail digital elevation model (NDH) [7]. The original source data was a LiDAR point cloud (LAZ 5 pts per meter), exported GeoTIFF images with 1 m resolution.

7.3.4 Feature/Vector Data

There were several features provided as part of the terrain data. Initially we used a public access database vbase [8] for the road network. We needed to create and alter some of the roads to fit the scenario, e.g., make sure some roads are unpaved.

As discussed in Section 4.4.2.2 it is important that an agreed upon data model is used for the vector data. For the demonstration, the TG used a data model that was largely based on the RIEDP standard that is currently in development, but where information was not available in RIEDP, yet it was added by the TG. See Annex D for an overview of the attributes that were used in the demonstration. All feature data was provided in the ESRI Shapefile-format, with the attributes according to the data model. These Shapefiles were then imported into the Terrain Service, so that the data could be served by the WFS interface.

7.4 WEATHER DATA USED IN DEMONSTRATION

The weather data used in the demonstration was provided by the Netherlands and comes from the ECMWF historical database. It covers the area shown in Figure 7-14 and was provided as a NETCDF dataset, containing 21 layers of weather information in hourly intervals. The data uses a grid with a resolution of 11 x 11 km. The data was provided for two historical days, that had weather matching the scenario used in the demonstration, 25 October 2019, and 3 December 2019.

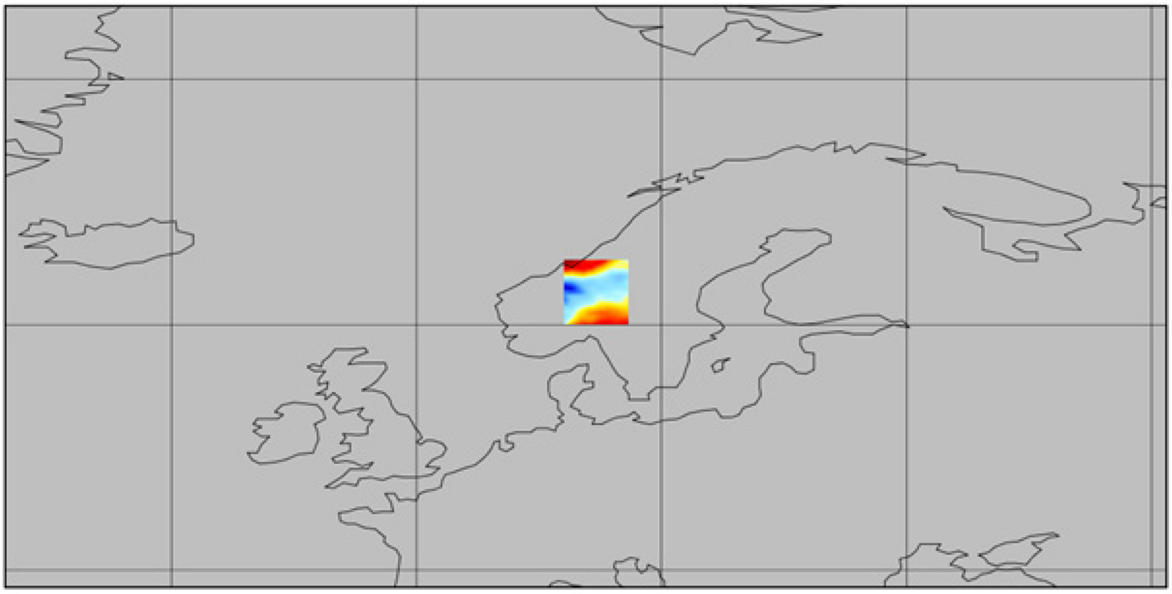

Figure 7-14: Coverage of the Weather Data Used.

The following data layers are included in the datasets:

- Cloud cover (low/medium/high);
- Cloud base height;
- Surface pressure;
- Temperature;
- Wind velocity;

- Precipitation;
- Snowfall;
- Snow density; and
- Snow depth.

Figure 7-15 shows the low cloud cover data as an example of the data.

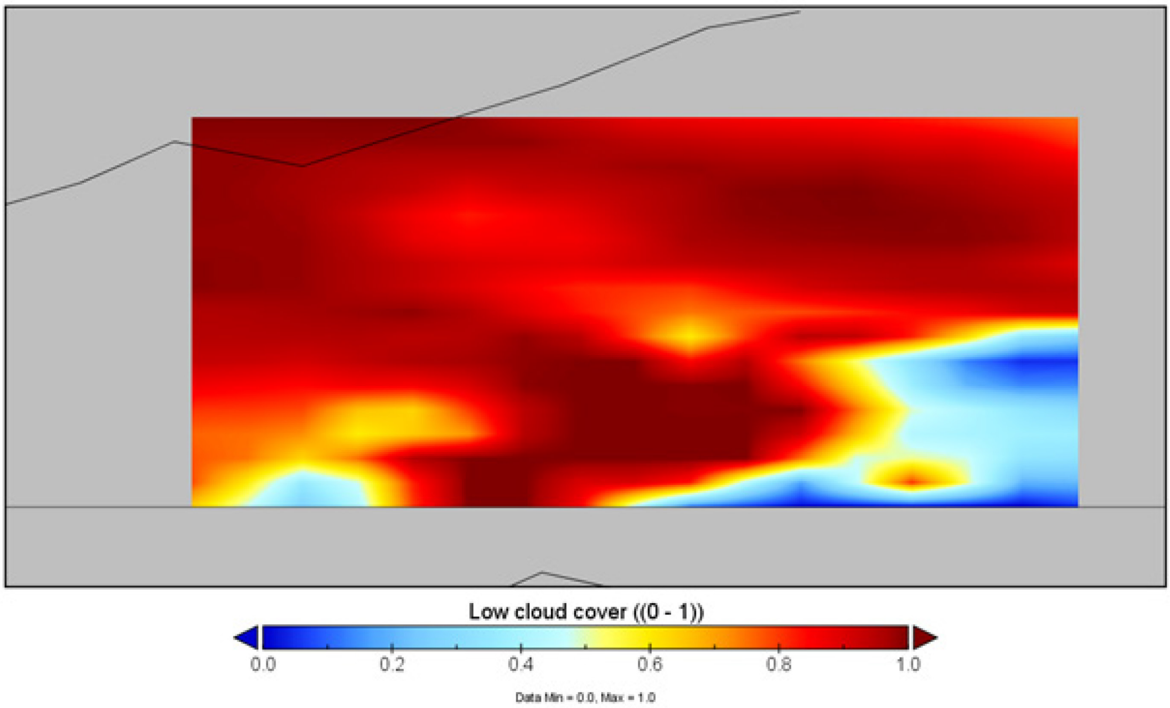

Figure 7-15: Example of Low Cloud Cover Data from the Dataset Used.

7.5 RESULTS AND LESSONS LEARNED

The Task Group had originally planned to perform the concept demonstration during a face-to-face meeting by connecting the various assets in a local area network. The COVID-19 crisis and resulting travel restrictions however prevented further face-to-face meetings from taking place within the timespan of the TG. Therefore, MSG-156 did perform the concept demonstration completely remote. The HLA tools offered by Sweden and Pitch were a great enabler for this, as it made the process of joining all assets in one federation much easier. Many Task Group members even participated in the concept demonstration from their home.

The primary result of the concept demonstration is that the Task Group has shown that the MSaaS based architecture to achieve a correlated dynamic synthetic environment is feasible. It has been possible to connect different federates to common services that provide information about the environment. And it has been possible to use central modification services to modify this environment dynamically during the simulation, where the federates were impacted by these changes in the environment. This shows that the foreseen benefits of a MSaaS based architecture are achievable and that the technology already exists nowadays to build an implementation of such an architecture.

However, it also must be noted that the MSG-156 concept demonstration should be seen as a first step in the development of the MSaaS DSE concept, as the scale of the demonstration was relatively small. The number of federates (if the supporting services are excluded) was only three: a vehicle simulator, a flight simulator and a Computer Generated Forces (CGF) tool. This means that this demonstration has not been able to test the challenges that will be encountered when trying to serve environment data in a large exercise with many federates. Especially for the Terrain Service, which needs to distribute larger volumes of data than the Weather Service, it might be a challenge to distribute all this data in a performant way. Possible solutions, like service replication and local caching of data, have not been evaluated in-depth as part of this concept demonstration.

Another limitation that the concept demonstration showed is that it is hard to implement such a MSaaS based architecture in existing or legacy simulation systems. All the federates involved in the concept demonstration needed modifications to be able to communicate with the DSE services. For example, adding a plugin to be able to interface with the Trafficability Service or adding an interface to be able to consume external weather data. In the Task Group the parties involved were either research institutes with access to the code of their systems or industry who developed such systems, so, in most cases, it was possible to make modifications to the systems. But this also shows that using existing or legacy systems without source-code access will be hard in a MSaaS based DSE architecture. And even with source access, the TG was not able to have each system support all the services, because the changes required were to fundamental and expensive. For example, not all participating federates were able to fetch the terrain data during run-time from the terrain service. This makes the transition to a MSaaS-based DSE architecture something for the mid-term future, as simulation systems first need to be equipped with the required interfaces.

The concept demonstration also shows that the NETN METOC FOM that is in development is useful in distributing weather data between simulation systems. Using this FOM it was possible to distribute weather data from the weather server to federates. But the demonstration also showed that just using the same FOM is not sufficient to have a common representation of the weather data. For example, for the clouds information on cloud layers was shared. For each layer, the type of cloud, the coverage percentage and the base and top altitude were shared. But this information is not sufficient to have a correlated representation of the clouds and the gaps in the clouds. This means that for simulation exercises where this level of correlation is required more agreements must be made beyond the usage of the METOC FOM. Either cloud algorithms have to be agreed on or, instead of cloud layers, individual clouds should be distributed from the Weather Service.

A key principle of a MSaaS architecture is that various services are connected and work together. But the MSG-156 concept demonstration also showed that such connections can lead to stability issues when systems are not robust enough for incorrect values that are distributed. For example, when the end of the weather source data was reached in the Weather Service, it would stop sending data. However, the flight simulator kept requesting data and would also receive answers. Once the Weather Service had reached the end of its data these values would however keep increasing until infinite. This was most likely due to extrapolation somewhere in the HLA communication. Having wind speeds that increased until infinite obviously resulted in stability issues in the flight dynamics, which are not designed to handle such extreme situations. This example illustrates that when various systems are connected in a MSaaS architecture it is important that they are robust for unexpected inputs, else the total simulation system might become less stable.

It proved to be a challenge for the Task Group to acquire the real-world weather data for the demonstration. The desired higher resolution data was not available freely and existing contracts between national MODs and meteorological offices did not include the delivery of such data for research projects. If such weather data is required for simulation exercises frequently it would make sense to include it in existing national contract or for NATO to provide access to such data for all participants.

Another challenge in requesting weather data is that as end user you need to specify which data you need, as the meteorological offices have a wide range of weather parameters available for delivery. So, depending on the aims of the simulation it should be defined which characteristics the weather should have, based on that a suitable day for the weather can then be selected. And based on the interactions in the simulation exercise it should be considered which weather parameters needs to be present in the data set at least, Section 5.1 provides information on the parameters that are most commonly used by simulation systems.

Concluding, the MSG-156 concept demonstration should be seen as a first proof of concept of a MSaaS-based DSE architecture and it has proven that the approach is feasible. Looking at the objectives of the Task Group it has been demonstrated that:

- Various federates can consume their terrain and weather data from central services, ensuring that they all use the same data and thereby reducing correlation issues.
- Modification services can be used to modify the terrain data centrally, thereby ensuring that all systems see the same dynamic changes to the environment.
- Consistent trafficability can be provided to the participants by having a trafficability service included, which calculates the influence of the current environment state on the trafficability for all participants.

However, an experiment on a larger scale should be performed to evaluate the performance and scalability of such an architecture. And, to allow future simulation systems to work in a MSaaS-based DSE architecture, they would need to have the interfaces to be able to communicate with the involved services, which requires that such interfaces become standardized.

7.6 REFERENCES

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Chapter 8 – SUMMARY AND CONCLUSIONS

Defence M&S systems currently provide limited representations of military operational environments. In the real world these environments are highly dynamic, where the state of the physical environment affects force behavior (e.g., effects of weather on ground vehicle mobility), and the effects of military physical (kinetic) force behavior affects the state of the environment (e.g., munition damage to buildings, infrastructure, etc.). Where dynamic elements are currently implemented in simulation systems, these are often carried out in a bespoke and pre-scripted manner, which limits the capability and scope for simulation interoperability.

In response to this, MSG-156 investigated methods, processes, and technologies to address the gap between the need to represent the challenges of the real-world operational environments in M&S systems and existing technical capabilities, with the objective to research how a correlated Dynamic Synthetic Environment (DSE) can be represented in future distributed simulations. MSG-156 has subsequently defined the following requirements for such a DSE architecture (see Table 8-1, Table 8-2 and Table 8-3).

Table 8-1: Requirements for a DSE Architecture.

REQ_DSE_1	It should be possible to make changes to the simulated environment at runtime during the simulation exercise.
REQ_DSE_2	It should be possible to have the dynamic environment changes triggered by: • Processes within the environment itself, e.g., weather affecting terrain conditions; • Events caused by participants of the exercise, e.g., the detonation of a weapon; and • The instructor or white cell operator of the simulation exercise.
REQ_DSE_3	The DSE architecture should support the inclusion of derived effects from the dynamic changes as well, e.g., destruction of a bridge is not only visual, but also affects the navigation of constructive entities.
REQ_DSE_4	The DSE shall be sufficiently correlated, so that different participants in the distributed simulation make the same assessment of the situation within the mission.
REQ_DSE_5	The DSE architecture should be vendor neutral.
REQ_DSE_6	The DSE architecture should use open standards in accordance with the NATO M&S Standards Profile (NMSSP) where appropriate.
REQ_DSE_7	The DSE architecture should support terrain and weather data for land and air operations. Data for underwater operations, sea states, space weather or other planets is out of scope for the TG. The DSE architecture should be flexible enough though, so that additional data layers can be added to the concept later.

Table 8-2: Requirements for Dynamic Terrain.

REQ_DT_1	The dynamic terrain should be represented consistently to the different participants in the simulation exercise, e.g., the presence of craters or the damage to objects.
REQ_DT_2	The dynamic terrain should have a consistent effect on entities and their systems in the simulation exercise, e.g., on their trafficability or line of sight.
REQ_DT_3	The damage to objects should be consistent with the characteristics of the weapon that caused the damage.

Table 8-3: Requirements for Dynamic Weather.

REQ_DW_1	The weather should change with time and space during the simulation exercise.
REQ_DW_2	The weather should be represented consistently to the different participants in the simulation exercise.
REQ_DW_3	The DSE architecture should support representing weather effects on entities and their systems consistently in the simulation exercise, e.g., trafficability of ground vehicles or on the performance of sensors.
REQ_DW_4	The representation of weather in simulation systems should support either historical or live weather data from authoritative data providers.

After surveying existing capabilities for dynamic environments in simulation systems and state-of-the-art technology and algorithms in simulation and entertainment gaming systems, the MSG-156 developed conceptual modelling diagrams to identify key interactions that needed to be supported within a DSE. Subsequent to this, a prototype MSaaS-based architecture was defined to enable dynamic elements of operational environments to be represented in a consistent manner across distributed simulations, see Figure 8-1.

The key concept in this solution architecture is that common services are responsible to manage and distribute environmental data within the simulation exercise. This includes use of a Terrain Service to obtain information about the terrain, and a Weather Service to obtain information about the weather. By having one service responsible for managing this data, many correlation risks are mitigated. Furthermore, when dynamic changes are made to the environment, one particular service is made responsible to perform these modifications, again eliminating correlation issues that occur when such modifications are being performed locally in each system. These modification services store the modified data in the Terrain Service, allowing all federates to access the changed data from there.

As part of de-risking the DSE architecture MSG-156 orchestrated a proof-of-concept demonstration, where federate simulations and services from the participating nations were selected, deployed, integrated, and executed in accordance with this architecture. Although the number of simulation federates and services available was limited, the demonstration proved the solution architecture to be feasible, and that such an architecture will help in ensuring that dynamic changes can be made and represented in a consistent way across distributed simulations. The demonstration proved that:

- Federate simulations can consume terrain and weather data from central services, ensuring that they all use the same data and thereby reducing correlation issues.

- Modification services can be used to modify the terrain data centrally, thereby ensuring that simulations systems see the same dynamic changes to the environment. The OGC standard for transactional services proved useful in enabling Modification Services to update terrain data in the Terrain Service.
- Consistent trafficability can be provided to the participants by having a trafficability service included, which calculates the influence of the current environment state on the trafficability for all participants.
- The NATO NETN METOC FOM that is in development is useful in distributing weather data between simulation systems.

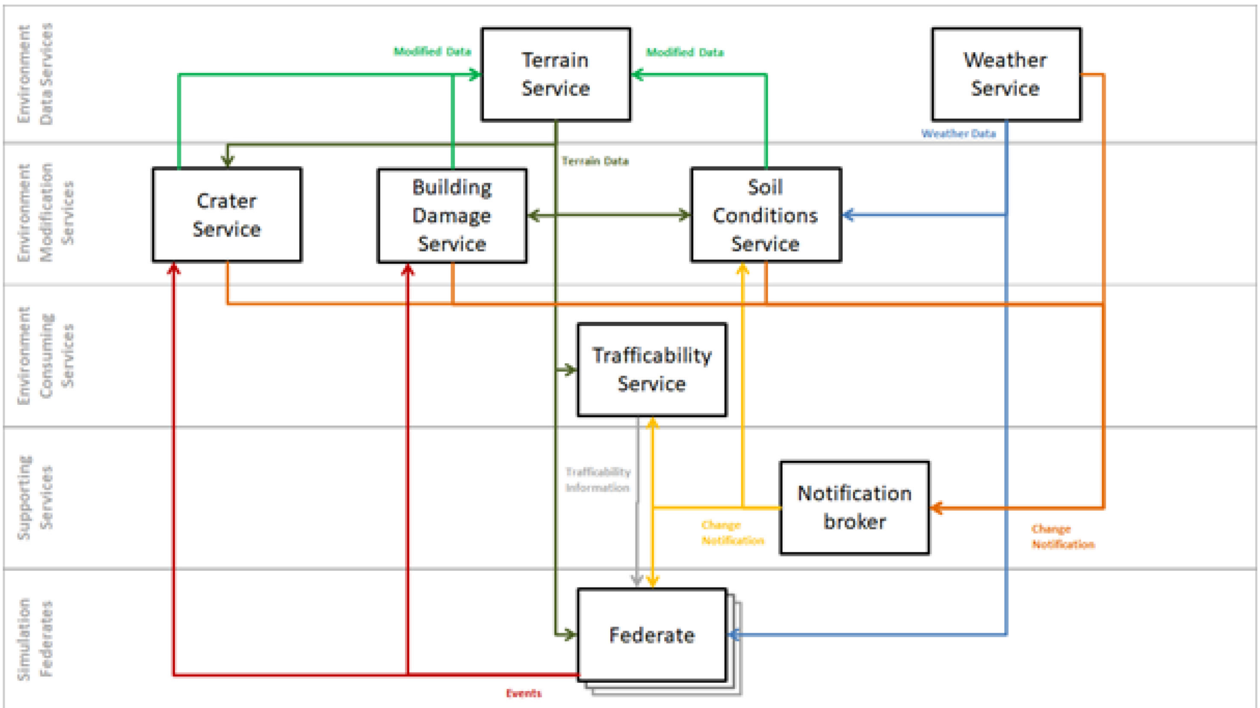

Figure 8-1: The Dynamic Synthetic Environment Architecture.

Within NATO a NATO Reference Mobility Model (NRMM) exists which includes the aspect of ‘trafficability’. This model is typically used for more operational applications, like mission planning. AVT-327 is developing a STANREC for the Next-Generation NATO Reference Mobility Model (NG-NRMM). Simulation is becoming more important in the work of AVT-327, so for the future it is foreseen that distributed simulation exercises might be able to benefit from the NG-NRMM model as well. The benefit of a Trafficability Service would be that the knowledge of the NG-NRMM model only must be implemented in one central location in the distributed simulation.

The de-facto standard for 3D model content, including the representation of features like buildings and bridges is the OpenFlight standard, while many systems also use their own proprietary formats. However, there is a need for a more modern standard for 3D content that supports streaming of the content from services and making dynamic changes to the content.

A standardized METOC FOM to exchange weather data alone is not sufficient to ensure correlated weather in a distributed simulation, because different simulation systems represent the weather differently, for example clouds can be represented as individual clouds or as cloud layers. This means that such a METOC

FOM should support these various representations, but also that a Weather Service will need to provide additional functionality to ensure correlation to the extent possible between these different representations.

The MSG-156 demonstration was a first proof-of-concept of a MSaaS-based DSE architecture and should be regarded as a first step in the development of the MSaaS DSE concept. The demonstration has also helped to identify which aspects of the architecture require further research to reach a level of maturity to be used in operational simulation exercises. This has led to the recommendations made by the MSG-156 TG, including a proposed way ahead.

Chapter 9 – RECOMMENDATIONS AND EXPLOITATION

Although the concept demonstration that MSG-156 performed was successful, the technology used in the proposed MSaaS-based DSE architecture is currently not yet mature enough to be implemented into operational simulation systems, MSG-156 does encourage other however to use the DSE architecture in future research and development activities. It is therefore recommended that NATO should carry out a larger scale experiment to evaluate how the solution architecture will perform in an environment where the services are stressed to a much larger extent. This could be part of a future NMSG task group or could be performed as part of an already planned distributed simulation exercise that involves MSaaS techniques.

The DSE architecture depends on standardized interfaces between the different services. Some of these interfaces are mature already, like the OGC interfaces to distribute geographical information. However, other interfaces would require more standardization, in particular:

1) The HLA FOM used to distribute METOC data. MSG-156 used the NETN METOC FOM that is in development. This FOM needs to support the various levels of fidelity that might be required for the weather representation. For example, not only cloud layers, but also individual clouds, which can be efficiently distributed.

2) The terrain server distributes vector data using a WFS interface. However, to allow efficient processing of the data it is recommended to use a standardized data model that describes the semantics and attributes of the features. Various attribution schemas exist, either in the GIS and M&S domain, but none covers all requirements of a DSE. The SISO RIEDP standard that is in development seems a promising standard to be used for such a data model in a DSE. Therefore, the recommendation is to ensure that further development of the RIEDP standard includes the requirements for a DSE.

3) The trafficability service has been identified as a new service that is needed to ensure consistent effects of the dynamic environment on the trafficability of vehicles. It is recommended to standardize the interfaces to this service, so that federates can support various implementations of such a service without requiring modifications. Related to this, it is also recommended to investigate how the work on the Next Generation NATO Reference Mobility Model (NG NRMM) can be integrated in a trafficability service, so the knowledge encapsulated in this model can be employed in distributed simulation exercises as well.

4) The investigation of a new format for sharing 3D content which supports the distribution and streaming of 3D model content to simulation systems, or for making dynamic changes to 3D model content during simulation execution time.

5) Various services working together require a mechanism to notify each other of changes. This requirement is not specific to DSE, but applies to any MSaaS solution. It is recommended that a common notification mechanism is developed for all MSaaS services, so that federates can easily switch between implementation of services without requiring changes.

In considering the above it is recommended for SISO to investigate how such open standards can best be developed. The existing SISO RIEDP PDG and Cloud-Based M&S (CBMS) might already cover some of these standards, while a new SISO Study Group (SG) might be needed to study how more DSE specific aspects can be addressed.

Outputs from MSG-156 should be used to inform activities carried out as part of the NATO MSG-193 Specialist Team on “Modelling and Simulation Standards in Federated Mission Networking (FMN)”.

Acquisition of real-world weather data proved to be a challenge for the TG. The desired higher resolution data was not available freely and existing contracts between national MODs and meteorological offices did not include the delivery of such data for research projects. If weather data is required for future simulation exercises, it is recommended to include this requirement in existing national contracts, or preferably for NATO to provide access to such data for all participants.

Once the above-mentioned aspects of the DSE architecture have been standardized, NATO nations can start to roll out the support for the DSE architecture in their operational systems. Given the paradigm change involved with this architecture, MSG-156 is aware that this will require quite extensive modifications to be made to simulation systems, which means that it can be hard for legacy systems to support this architecture. Introducing a DSE is therefore more straightforward in new simulation systems or during major upgrades of existing systems.

Once sufficient simulation systems support the DSE architecture, NATO should consider providing and hosting the key services that are needed for a DSE. If NATO would provide a terrain service, weather service and various modification services to NATO nations, the burden of setting up a distributed simulation exercise featuring a DSE would be significantly lowered.

Annex A – SURVEY QUESTIONNAIRE

Name	
Description	
Supplier	
Customer	
Fielded	
POC	
Operational relevance	
Weather effects (e.g., wind, clouds, temperature)	
Natural effects on environment (e.g., flooding, effect of rainfall on trafficability)	
Human geophysical effects on environment (e.g., digging, dredging)	
Force engagements effects on environment (e.g., craters and object damage)	
Limitations of the system	
Scope of interoperability	
Standards used	
Additional user/technical requirements not fulfilled by system	
References	

Annex B – SOIL CONDITIONS SERVICE MODEL

In this section, we explain the model used in the demonstration, which calculates the effect of precipitation on the terrain soil. The goal is not to model and simulate the complete water cycle of water on earth, but rather from precipitation (rain) to the evaporation and uptake from the ground. Therefore, we do not model groundwater flow or aquifers (Figure B-1).

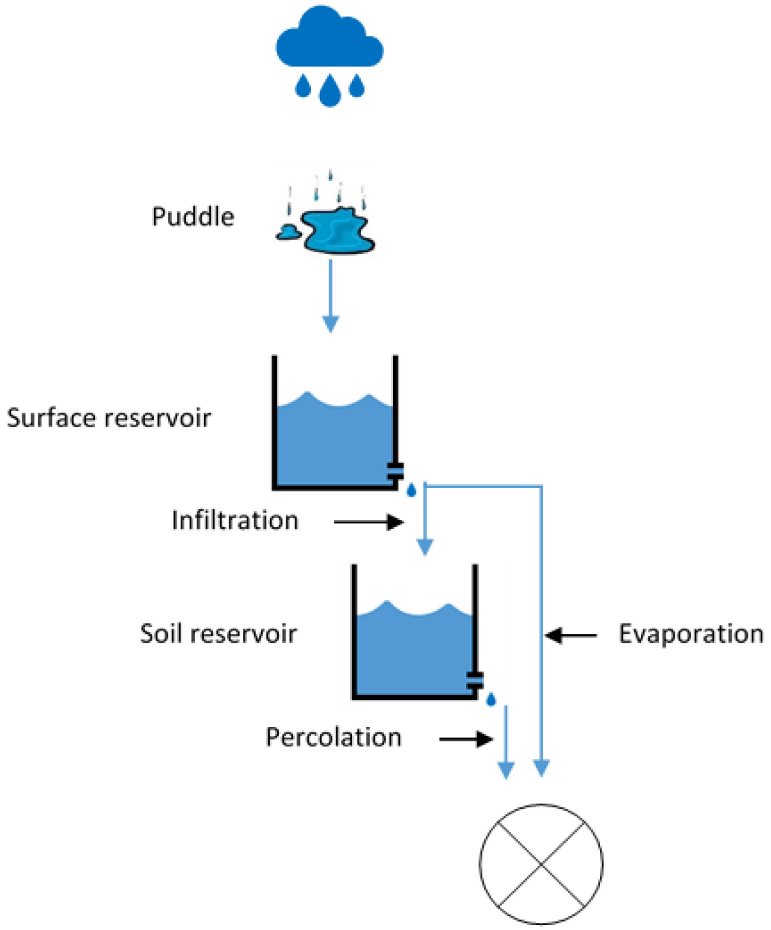

Figure B-1: Soil Condition Model.

The most important aspects of the model are:

- The surface becomes wet and dry, depending on the rain and surface properties. Other services (such as a trafficability service) can utilize this wetness to alter surface interaction properties.
- Puddles form and deplete, depending on the surface properties.
- The excess water in puddles, streams and lakes can flow across the terrain according to physics.
- Computations for large areas must be done in real time or faster.
- The model must be valid for small time steps.

These aspects are focused on the simulation of rain and its effects within the span of a few hours or days, which is a typical duration of a simulated scenario for training purposes. Hereby, we have chosen to neglect effects that transcend this duration, such as soil slippage, soil deposit and mixing of soils.

Many hydrological models use the runoff curve number. This number is a property of the surface type and with it one can calculate (estimate) the amount of direct runoff from the amount of rainfall. However, the formula is nonlinear, meaning that the runoff from 5 inches of rain is not the same as the runoff from 3 inches of rain followed (sometime later) by 2 inches of rain. Simulating small time steps means that the rainfall will be discretized in time, and one must deal with this nonlinear effect. Therefore, we have chosen a different approach.

First, we have chosen to represent the terrain with a grid. Grid calculations are fast (in comparison to particle-based systems) and allow to choose a different grid resolution when needed. Second, each grid cell simulates its own dynamical system, applying infiltration, evaporation, and percolation of water by the ground. Grid cells do not influence each other's state (no groundwater flow), allowing processing in parallel of all grid cells. Excess water for the grid cell is added as a puddle (on top of the terrain surface) to that grid cell. Third, all water in puddles can flow to neighboring grid cells in the waterflow step. This waterflow of puddles will eventually create small streams of runoff water that flows to rivers and lakes. We divided the rainfall model in two steps: absorption of the water by the ground and letting the water in the puddles flow to neighboring grid cells. Therefore, simulation of the rain is done by repeating the following steps (for a given delta time):

1) Obtain current rainfall per grid cell.
2) Apply water absorption.
3) Apply waterflow.

B.1 ABSORPTION

The absorption of water into the terrain is done on a grid cell basis. In each grid cell, the rainwater that is added will slowly be absorbed by the ground according to the parameters of that grid cell, which are independent of other grid cells.

The dynamical system that simulates the absorption process in each grid cell is a linear reservoir model with two reservoirs. Each reservoir has a maximum size. The water in the reservoir cannot exceed that size. The removal of water from the reservoirs is done by solving the linear first order differential equation $\frac{dS(t)}{dt} = kS(t)$ where S is the amount of water stored, t is time and k is a constant controlling the removal of water. For the reservoirs, the k is negative. This simple model can be solved explicitly and can thus be evaluated for a given delta time.

We call the first reservoir the surface reservoir, as it models the amount of water the vegetation and top layer of the surface can store. From this reservoir the water infiltrates deeper into the ground or evaporates into the air. We call the second reservoir the soil reservoir, as it resembles the storage of water that infiltrated the ground.

Each grid cell has the following properties, where all constants and maximums have been configured based on the surface type of the terrain cell:

1) **Puddle height**: the amount of water that forms in a puddle on top of the terrain.
2) **Surface reservoir maximum**: the maximum amount of water that the surface reservoir can hold. More water will be removed as excess water.

3) **Surface reservoir current amount**: the current amount of water in the surface reservoir.
4) **Soil reservoir maximum**: the maximum amount of water that the soil reservoir can hold. More water will be removed as excess water.
5) **Soil reservoir current amount**: the current amount of water in the soil reservoir.
6) **Evaporation constant**: constant controlling the removal of water from the surface reservoir out of the system.
7) **Infiltration constant**: constant controlling the removal of water from the surface reservoir into the soil reservoir.
8) **Percolation constant**: constant controlling the removal of water from the soil reservoir out of the system.

For each grid cell the absorption for a timestep is updated by:

1) Add rainfall amount to the surface reservoir.
2) Excess water in the surface reservoir is moved to the puddle.
3) Soil reservoir water is reduced according to the percolation.
4) Surface reservoir water is reduced using infiltration and evaporation constants. The water is moved to the soil reservoir and out of the system, respectively.
5) Excess water in the soil reservoir is moved to the surface reservoir.
6) All puddle water is moved to the surface reservoir.
7) Excess water in the surface reservoir is moved to the puddle.

The configuration of all the properties for this model will not be discussed in detail. However, we do like to note some possible configurations and the effects they have. We used the surface type to configure the properties. For example, the surface type rock can be modeled with a smaller surface reservoir maximum and a low evaporation (there is no vegetation). This will create puddles since the infiltration of the water will be the bottleneck in this grid cells system.

For rivers and lakes (‘water’ surface type) we need to apply some special configurations, otherwise the water will eventually be removed from the terrain (leading to empty rivers). For these grid cells we set the surface reservoir maximum to zero, such that no water will be removed. Then we must make sure that the height of the terrain for the water areas is lower than the surrounding grid cells, so the runoff water will flow into the rivers and lakes. Also, the terrain should be initialized with existing ‘puddles’ at the location of water (equal to the dept of the water), otherwise the scenario would start with empty rivers and lakes. Finally, we like to note that a river and lake could overflow during the scenario due to the runoff water. Of course, this could be counteracted by increasing the volume of the river (lowering the initialized ‘puddle’) or putting a special ‘riverbank’ surface around rivers, which can absorb and remove a lot of water.

B.2 WATERFLOW

There are many methods to simulate the flow of water. We have chosen to implement the method by Maes et al. [1]. It uses a grid-based representation of the water (puddle) layer. A brief explanation of the model will be given here. Details can be found in their paper.

The model is called a water column model. In each grid cell the water (the ‘puddle’ layer) lies on top of the surface. The differences in net height (terrain height + puddle height) of neighboring grid cells causes pressure between these cells. Between neighboring grid cells a (virtual) pipe exists, through which water can flow. The pressure difference leads to a positive or negative acceleration of the water in the pipe.

The resulting velocity in the pipe determines the amount of water that moves from one cell to its neighbor. In our implementation the water exists of one layer (in the model multiple are possible) and between neighboring cells there is one pipe (in the model multiple are possible) through which water can flow from one grid cell to the next.

B.3 MODEL IMPROVEMENTS

Although the model in its current state is adequate for the purposes of supporting dynamic trafficability, there are many improvements possible to increase its realism. However, each improvement creates a more complex system with more parameters to be tuned.

Currently, the features on the terrain, such as buildings, have no interaction with the rainfall. One could alter the (input) rainfall amount at locations where buildings exist, possibly removing water that is directed to a sewer or adding water around such features (e.g., the water flows over the roof and is dropped besides the building). To incorporate these features accurately, the elevation data should be changed to include features such as building (i.e., using a Digital Surface Model instead of a Digital Terrain Model).

Other improvements could be to incorporate the strength of the sun, which increases the evaporation constant. Similarly, the vegetation will absorb some water with their roots, which could also be modeled.

Lastly, all parameters must be tuned manually. It would be better to configure the parameters using real-world datasets.

B.4 REFERENCES

[1] Maes, M., Fujimoto, T., and Chiba, N. (2007). Low-Memory and Interactive-Rate Animation of Water-Column Based Flows. The Journal of The Society for Art and Science, 7, 1-13.

Annex C – TRAFFICABILITY SERVICE MODEL

The model that is implemented in the trafficability service is based on the information in 'Soils trafficability is the capacity of soils to support military vehicles' [1]. This information is rather operational (e.g., containing field measurements) and not specifically created for simulation purposes. In this section we will briefly explain the major aspects of the model and highlight the changes that enable the model to be simulated.

First, we must discuss the responsibilities of the model: which effects are incorporated in the model and which effects are still to be simulated by the individual simulators. This trafficability model is about the soil conditions and its effect on the maximum speed of a vehicle. Features (e.g., buildings) and vegetation are not taken into account by the model and physics interactions such as collisions should still be handled by the individual simulators. Therefore, the maximum speed of a vehicle that is a result of this model should be seen as an upper boundary of the speed and simulators should deviate from that when the need arises. Another influence on the trafficability is the driver's skill and behavior, which is beyond the scope of this model.

The model does account for the following effects:

- Is the soil able to bear the vehicle?
- Slope of the terrain.
- Is there enough traction (slip effect)?
- Are there tracks in the ground made by preceding vehicles?

The information that the model uses can be summarized as vehicle-related and soil-related. The vehicle properties are:

1) Maximum speed.
2) Maximum slope traversable.
3) Maximum speed when traversing the maximum slope.
4) Whether the vehicle is tracked or wheeled.
5) Vehicle Cone Indexes (VCI(1) and VCI(50)): these are the Vehicle Cone Indexes for one pass and fifty passes for a given vehicle. The shear resistance of the local soil is often measured in the real world using a cone penetrometer device and expressed in terms of a Cone Index. A VCI, or Vehicle Cone Index, is the shear resistance of the soil required by the vehicle to be able to traverse the soil. The different VCIs can be calculated from numerous other vehicle properties (e.g., weight, number of wheels/tracked surface, engine power, etc.).

The soil properties are:

1) Slip effect: three constants between zero and one summarizing how much a vehicle will suffer from slip when the soil is dry, moist, or wet.
2) Track effect: two constants between zero and one summarizing how much a vehicle will suffer from tracks created by traffic in front when the vehicle has wheels or tracks.
3) The Cone Index (CI) of the soil.
4) Two Remolding Indices (RI), one for a dry soil and one for a wet soil.

The calculation of the VCI(1) and VCI(50) properties is given in the information document and uses detailed vehicle information. The slip and track effect constants are inspired on Table 7-6 from Ref. [1], where we translated terms such as 'slight' to a constant. The cone indices and remolding indices of soils can be extracted from Table 7-8 from Ref. [1].

The final piece of information required by the model is a list of vehicles that have driven on the same piece of terrain shortly before the current vehicle. This information is needed to derive whether tracks have formed and whether the soil can carry the current vehicle. In short, the vehicles driving in the rear of a convoy will have more difficulty (lower maximum speed) traversing the terrain.

The model can be summarized as follows:

1) **Maximum speed**: The maximum speed of a vehicle on the slope is calculated.
2) **Soil effect**: The effect of whether the soil can bear the vehicle is calculated.
3) **Slip effect**: The effect of possible slip is calculated.
4) **Track effect**: The effect of possible existing tracks is calculated.
5) The resulting maximum speed is the minimum of the above three effects multiplied by the maximum speed.

We decided that, for practical reasons, vehicles in the scenario should never be truly stuck (maximum speed of zero) and therefore we return at least a speed of 5 m/s.

C.1 MAXIMUM SPEED

We estimate a maximum speed that a vehicle can sustain on a given slope. We do not factor in any soil properties; this is done in the soil effect calculation. For downhill slopes, the maximum speed is the maximum speed of the vehicle. Note that for steep downhill driving it may not be safe to drive that fast.

For uphill driving the reality is complex and probably the gears of the vehicle have a lot of influence. For our simulation it is important that steeper slopes result in a lower maximum speed, and although this relation is probably not a linear one, we do model it as such. Therefore, the maximum speed is linearly interpolated between zero slope (with value the maximum speed of the vehicle) and the maximum slope (with corresponding speed value).

C.2 SOIL EFFECT

In summary, this effect is calculated by subtracting the Remolded Cone Index (RCI) of the soil with the required shear strength of the current vehicle passing over the soil. This shear strength is a result of vehicle properties, the slope and the vehicles that have driven on the soil before the current vehicle. The resulting number is an indication of whether the vehicle can pass the terrain: negative means it is unpassable, small positive means it can be traversed with difficulty and large positive means there will not be any problems.

To obtain the RCI value of the soil, the RI of the soil is calculated by linearly interpolating the wet and dry RI values of the soil using the current wetness level of the soil (which is influenced by the weather). This RI is then multiplied by the CI of the soil to obtain the RCI.

For each vehicle in front of the current vehicle and for the current vehicle, a delta VCI is calculated (using (VCI(50) – VCI(1)) / 49). We calculate the VCI(n) of the current vehicle as the VCI(1) of the vehicle with the largest VCI(1) plus all the delta VCI's for all other vehicles.

Next, the pass number (n) is calculated. When all vehicles in front of the current vehicle are the same as the current vehicle, the pass number is simply the number of vehicles in front of the current vehicle plus one. However, note that when vehicles in front have different values for VCI(1) and VCI(50), the pass number should be different. We calculate the pass number with (VCI(n) – VCI(1)) / delta VCI (where VCI(1) and delta VCI are taken from the current vehicle).

Next, we incorporate the effect of the slope. For downhill driving no additional shear strength is required, but for uphill driving Figure 7-7 (for fifty passes) and Figure 7-8 (for one pass) from Ref. [1] contain a graph mapping the slope to an amount of extra required VCI. Using the slope and these graphs we obtain an extra amount of VCI for one and fifty passes. Using the pass number, we linearly interpolate (or extrapolate) these numbers to obtain the extra required VCI for driving uphill.

Finally, we calculate the net shear strength (RCIx(n)) by subtracting from the RCI the VCI(n) and extra slope VCI. This RCIx(n) value is translated to a speed multiplication factor ([0 … 1]). For this the RCIx(n) is divided by a chosen constant of value 20 and clamped between 0 and 1. Any other value for this constant could have been chosen, as long as the effect of soil weakening is slowly changing and not instantly degraded to zero.

C.3 SLIP EFFECT

For each soil type there are three slip effects (dry, moist and wet). The current wetness of the soil is retrieved and the resulting value for the slip effect is obtained by (again) linear interpolation between the three slip effects.

When driving downhill, it can be argued that this slip effect should be less (one will move forward even though the vehicle is slipping). We have incorporated this by reducing the slip effect for downhill driving.

C.4 TRACK EFFECT

Similar to the slip effect, the track effect should become worse when the moisture in the soil increases. When the soil is saturated with water, the track effect should be equal to the value given in the soil property (for a wheeled or tracked vehicle). The moisture level of the soil is used to interpolate and find a value that fits the current soil condition.

When there are no vehicles in front of the current vehicle, no tracks are present and thus there should be no effect. The number of vehicles in front is counted and when there are no vehicles in front, the track effect is set to one (no effect). When there are ten or more vehicles in front, the track effect is set to the value obtained above. Values between zero and ten are linearly interpolated, leading to a continuous increase in the effect when more vehicles are driving in front. Again, the constant with value 10 is a somewhat arbitrarily chosen constant, but it is important that the track effect slowly builds up.

C.5 REFERENCES

[1] Gerretsen, A., Smelik, R.M., Smith, N. and Ly Van, K. (2020), A Proof-of-Concept Demonstration of Dynamic Synthetic Environments in Distributed Simulation. NATO MSG-177 Virtual Symposium, October 2020, poster presentation.

Annex D – ATTRIBUTION OF VECTOR DATA IN DEMONSTRATION

This annex gives an overview of the attributes that were used in the vector data for the demonstration (Table D-1). As discussed in Chapter 7 the data model for the attributes is largely based on the RIEDP standard.

Table D-1: Attribution of Vector Data in Demonstration.

Data Layer	RIEDP Feature	Required Attribute	Attribute Required for	RIEDP Attribute
Surface type [polygon]	GRASS_LAND BOG TREED_TRACT BRUSH_LAND BUILD_UP_REGION CROP_LAND PARK QUARRY WATER_BODY LAND etc.	Surface material	Trafficability calculation, terrain-weather interaction modifications of surface conditions	SURFACE_MATERIAL_TYPE
Vegetation [polygon]	TREED_TRACT BRUSH_LAND	Vegetation type	Correlated visual representation	VEGETATION_TYPE
		Vegetation density	Correlated visual representation	VEGETATION_DENSITY
Road [line]	ROAD	Surface type	Trafficability calculation, correlated visual representation	SURFACE_MATERIAL_TYPE
		Number of lanes	Routing service	PATH_COUNT
		Maximum speed	Routing service	VEHICLE_SPEED_LIMIT
		Width	Correlated visual representation	WIDTH
		Bridge	Routing service	BRIDGE_PRESENT
		Damage state	Routing service, correlated visual representation	FUNCTIONAL_STATUS

Data Layer	RIEDP Feature	Required Attribute	Attribute Required for	RIEDP Attribute
3D model placement [point]	BUILDING	Model file	Correlated visual representation	LINKTO_3DOBJECT
		Orientation	Correlated visual representation	ORIENTATION_ANGLE
		Damage state	Correlated visual representation	FUNCTIONAL_STATUS

Remarks:

1) The surface type and vegetation layers do overlap, in the sense that vegetation is part of the surface type as well.

The enumeration for the VEGETATION_TYPE is given below. RIEDP contains more possible values, only those that are used in the MSG-156 dataset are listed:

1) ALPINE_TUNDRA
2) BAMBOO
3) BIRCH
4) BRUSHLAND_MEDIUM_TO_DENSE
5) BRUSHLAND_OPEN_TO_MEDIUM
6) CITRUS
7) CONIFER
8) CYPRESS
9) DECIDUOUS_UNSPECIFIED
10) DRY_CROPS
11) EVERGREEN_UNSPECIFIED
12) GRASS
13) GROVE
14) HARDWOOD
15) MANGROVE
16) MARSH
17) MIXED_CROPS
18) MIXED_TREES
19) NON_TREED
20) OAK
21) PALM
22) PEAT

23) RICE_FIELD
24) SEA_GRASS
25) SYSTEMATIC_PLANTING
26) TROPICAL_GRASS
27) TUNDRA
28) TUNDRA_BUSH_SCRUB
29) TUNDRA_HERBACEOUS
30) TUNDRA_WET
31) VINEYARDS_HOPS_GINSENG
32) WET_CROPS
33) WHEAT

The enumeration for the SURFACE_MATERIAL_TYPE is given below. RIEDP contains more possible values, only those that are used in the MSG-156 dataset are listed:

1) ALUMINUM
2) ASH
3) ASPHALT
4) BASALT
5) BRICK
6) CEMENT
7) CLAY
8) COAL
9) CONCRETE
10) CONGLOMERATE
11) COPPER
12) CORAL
13) EARTHEN
14) GRASS
15) GRAVEL
16) ICE
17) METAL
18) MUD
19) OIL
20) PAINT
21) PEAT
22) PERMANENT_HARD

23) ROCK
24) SALT
25) SAND
26) SAND_GRADED_ROLLED_OILED
27) SANDSTONE
28) SEWAGE
29) SILT
30) SNOW
31) SOIL
32) STEEL
33) STONE
34) THATCH
35) TREED_VEGETATION
36) VEGETATED_WETLAND
37) WATER
38) WOOD

Surface type data is also available in raster (GeoTIFF) format, derived from the surface type polygons. This raster is a single-channel raster containing 8-bit indices to a table of surface types. Table D-2 is used.

Table D-2: Surface Type Data.

Index (Pixel Value)	RGB	Surface Type
3	80, 80, 80	asphalt
13	153, 102, 51	**earthen**
14	**241, 239, 218**	**grass**
15	**255, 230, 153**	**gravel**
18	**1, 176, 165**	**mud**
23	**172, 185, 202**	**rock**
37	**142, 169, 219**	**water**
38	**84, 130, 53**	**wood**

The enumeration for the FUNCTIONAL_STATUS is given below. RIEDP contains more possible values, only those that are used in the MSG-156 dataset are listed:

1) DAMAGED
2) DESTROYED
3) OPERATIONAL
4) PARTIALLY_DESTROYED

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14. Abstract

In contrast to real world environments, synthetic environments used in distributed military simulations are often static and unable to represent changes in a consistent way, e.g., changes due to deteriorating weather conditions or combat engineering during scenario execution. To better train and prepare military personnel for dynamic real-world conditions, the synthetic environment needs to support such dynamic modifications in a standardized and interoperable way to provide a consistent representation across dissimilar simulation systems. The objective of MSG-156 is to define best practices, required methodologies and technologies and requirements for standards needed to achieve a correlated dynamic SE in future distributed simulation exercises.

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