Techniques for Representation and Usage of Mission-centric Value of Information

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ABSTRACT

Future Operational Environments (OEs) for Command and Control (C2) will be defined through increasing complexity of battlefield assets, their diversity, and their interactions. For Opposing Forces (OPFOR), tactics, techniques, and procedures may be carried out in environments rich in neutral (CIV) assets, as commonly reflected in Asymmetric Warfare scenarios. Growth in available battlefield information and source variety can place strain on both the attention and cognitive load of battlefield personnel. Approaches for calculating Value of Information (VoI) of Information Objects represent a growing focus area for C4ISR research.

For military personnel, novel methods are becoming necessary to facilitate review of VoI assessments. From the perspective of Human-Information Interaction, advances in tools for VoI assessment review stand to improve personnel understanding of prioritization strategies, as well as enable fine-tuning of VoI calculation inputs (e.g., user preferences) to achieve desirable content prioritizations.

This work investigates Knowledge Graphs as a representation medium for mission-centric VoI assessments. Through representation of content in triple form (<*Subject*, *Predicate*, *Object*>), Knowledge Graphs can facilitate both integration of knowledge structures and relationship-centric querying by personnel. To facilitate structuring of Knowledge Graph content, a modular ontology termed **Mission-VoI** is proposed for capturing details on mission history, user content delivery preferences, and VoI reports for individual Information Objects.

To help illustrate the usage of Mission-VoI within Knowledge Graphs, sample encodings are provided around a simple battlefield information management scenario. Following from this, discussion of Knowledge Graph querying use cases is provided, along with a review of envisioned follow-on HII research.

Keywords: Value of Information
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1. Introduction

Modern battlefield environments offer Soldiers a growing volume and variety of information to support mission tasks. Such information may come from a variety of sources, ranging from traditional Human Intelligence (HUMINT) and sensor networks, to emerging Internet of Things (IoT) and social media platforms. These content sources may change as a function of ongoing mission events. For example, a sensor network may be damaged by opposition force (OPFOR) activity and subsequently repaired by friendly (OWNFOR) forces. As such, the ability of sources to generate actionable information may vary as a function of time and battlefield activities.

Growth in available battlefield information and source variety can place strain on both the attention and cognitive load of battlefield personnel. Additionally, constraints presented by tactical-edge networks must be accounted for in selecting information to disseminate. Hence, methods become required to filter and prioritize units of information – termed *Information Objects* – according to the needs of particular consumers. Methods for calculating Value of Information (VoI) represent a growing focus area for C4ISR research, with growing interest on applying mission knowledge tied to particular consumers [1]. In previous efforts (e.g., [2]), VoI has been calculated through collections of *evaluation metrics* to review the content of an Information Object against a consumer's needs and preferences. Such calculations can become difficult to interpret due to the complexities of mission tasks and their information requirements, combined with the dynamic state of Information Object producing sources.

For military personnel, novel methods are becoming necessary to facilitate review of VoI assessments. From the perspective of Human-Information Interaction [3], advances in tools for VoI assessment review stand to improve personnel understanding of Information Object prioritization strategies, as well as enable fine-tuning of VoI calculation inputs (e.g., user preferences) to achieve desirable content prioritizations.

Knowledge Graphs[1] represent an emerging approach for storing and cataloguing domain knowledge, as a means of enriching search and decision support systems. This work investigates Knowledge Graphs as a representation medium for mission-centric VoI assessments. Through representation of content in triple (<*Subject, Predicate, Object*>) form, Knowledge Graphs can facilitate both integration of knowledge structures and relationship-centric querying by personnel. To facilitate structuring of Knowledge Graph content, a modular ontology termed **Mission-VoI** is proposed for capturing the following information:

(1) **Mission History Record**: encodes both histories of assets through the course of a mission, as well as records of task assignments to personnel.
(2) **User Profile**: captures user preferences on the relevance of different VoI evaluation metrics to their needs.
(3) **VoI Report:** encodes details of the VoI scoring for a particular Information Object relative to a consumer's preferences. Each VoI report is linked to a: (I) particular User Profile; (II) a particular generating source at a specific point in time, as defined in the Mission History Record.

To support encoding of mission histories, the existing Missions and Means Framework (MMF) ontology [4] is extended and integrated with Mission-VoI to support representation both mission domain knowledge and events. Key contributions of the Mission-VoI ontology are as follows:

- Alterations are provided to MMF model to formally establish links between Information Objects and generating sources (defined in MMF terminology as *components*).

[1] https://googleblog.blogspot.co.uk/2012/05/introducing-knowledge-graph-things-not.html

- Representation of MMF component versions at different points in time, to aid in capturing the impact of battlefield events on Information Object generating sources.
- Representation of user profile versioning, to establish the impact of consumer preference shifts on VoI assessments.

To help illustrate the usage of Mission-VoI within Knowledge Graphs, sample encodings are provided around a simple battlefield information management scenario. Following from this, discussion of Knowledge Graph querying use cases is provided, along with a review of envisioned follow-on HII research.

The remaining sections are organized as follows. Section 2 reviews both the MMF model and provides foundational discussion on VoI assessment. Section 3 provides expanded detail on the Mission-VoI ontology, covering individual modules for representing: Mission History Records, User Profiles, and VoI Reports. Section 4 then provides sample Mission-VoI Knowledge Graph encodings, centered on a battlefield information management scenario. Section 5 outlines current HII research challenges tied to this work, followed by concluding remarks in Section 6.

2. Foundational Work

In this section, a review of relevant VoI efforts will be discussed, followed by an introduction to the MMF and MMF ontology. Extensions to these efforts will then be discussed in Section 3.

2.1 Value of Information

In prior research, Value of Information has been defined along the notion of intrinsic vs extrinsic attributes of Information Objects.

Intrinsic attributes can be viewed as measuring the inherent quality of an Information Object, and will vary based on the type considered. For example, an Information Object corresponding to image data may have intrinsic metrics corresponding to *image resolution*, *presence of noise*, or *presence of distortion*. By themselves, intrinsic attributes can be viewed as capturing Quality of Information (QoI) [5] for a particular Information Object. Likewise, *extrinsic attributes* measure the utility of an Information Object for a particular consumer as a function of their needs. Examples of extrinsic attributes could include geographic relevance (i.e., does this come from a mission-relevant location) as well as temporal relevance (i.e., will I need this soon for my mission tasks)? An additional type of extrinsic attribute could measure likely presence of relevant information. For instance, in a particular image, how likely is there information of relevance to a mission task depicted? For purposes of this work, VoI assessments are seen as building upon QoI assessment, leveraging extrinsic attributes in-parallel with intrinsic attributes.

Quantitative scoring of VoI has previously [2] been calculated through weighted averages of *evaluation metrics*, with each metric corresponding to a particular Information Object attribute. With respect to calculation of evaluation metric values, two types of methods noted in prior work [6] are *function-based* and *knowledge-based* assessment. Here, function-based assessment applies mathematical functions to assess a metric's value, based on both Information Object attributes and consumer context. Here, metric assessment functions could include measurements of geospatial or temporal relevance of an Information Object to a consumer. Likewise, knowledge-based assessment relies upon evaluation of Information Object attributes against a particular consumer's context (e.g., mission and environmental conditions) through the use of supplemental domain knowledge. For instance, images from infrared sensors – as opposed to visible light sensors - may be more valuable at night, based on supporting knowledge of appropriate environment-sensor pairings.

For VoI assessment systems, knowledge-based comparison is seen as having a particularly rich set of research challenges, rooted in development and validation of appropriate knowledge base content. Current challenges in this area include development of effective models for both Soldier context (e.g., concerning mission status and environmental/physiological factors) as well as mission state [1]. Towards representing mission state, including mission tasks and events, recent efforts tied to the Missions and Means Framework are of particular relevance.

2.2 Missions and Means Framework (MMF)

The Missions and Means Framework (MMF) [7] represents a generalizable model for mission planning and simulation, rooted in the previously-established Military Decision Making Process (MDMP) [8]. Originally developed for modeling kinetics-based missions, the MMF has since been applied to the domain of sensor assignment to missions [9] and is now actively being considered for use in Intelligence, Surveillance, and Reconnaissance (ISR) support systems [10].

Mission planning and simulation in MMF center on *task cycles*, as shown in Figure 1.

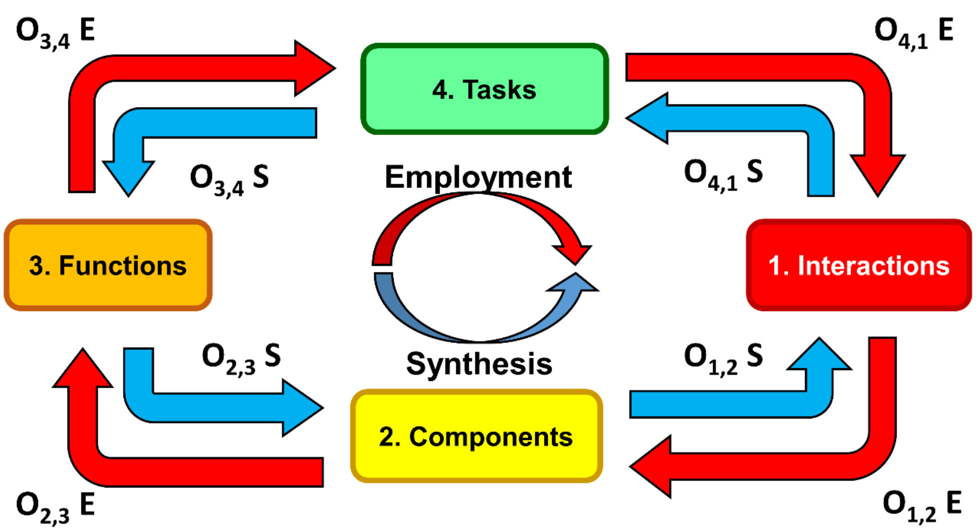

Figure 1: Depiction of MMF task cycle (adapted from [6]).

MMF defines two task cycle types:

- **Mission Employment:** Time-forward cycles (shown in red) which represent mission execution or simulation.
- **Mission Synthesis:** Time-backward cycles (shown in blue) which represent mission planning.

Four types of information (termed *Levels*) are represented:

- **Level 4:** Tasks to be performed within a mission.
- **Level 3:** Operational functions needed to achieve mission tasks.
- **Level 2:** Specific components, each possessing different capabilities.
- **Level 1:** Interactions carried out in the Operational Environment via execution of mission tasks, which impact the state of components in the environment.

In turn, Operators (links between individual Levels) establish mappings between level members. For example, in a mission planning exercise, consider the Level 4 task of *being on the lookout for insurgents planting IEDs along nearby roads*, requiring a corresponding Level 3 capability (e.g., providing personnel information on sightings of insurgent activities on nearby roads). To achieve this Level 3 capability, a review of Level 2 components can be made, each with varying capability to deliver the needed information (e.g., imaging sensors in nearby proximity). Following the Level 2 component review, selected components are mapped back to the Level 3 capability with varying match scores corresponding to estimated utility. Likewise, for a corresponding mission execution or simulation, available Level 2 components would be mapped to known Level 3 capabilities, in-turn matched to Level 4 mission tasks.

To support both Mission Employment and Mission Synthesis, two different classes of MMF Operators are defined: *Synthesis Operators* for Mission Synthesis, and *Employment Operators* for Mission Employment.

The MMF Employment Operators can be defined as follows:

- **$O_{1,2}$ E:** Applies Level 1 Operational Environment interactions to specific Level 2 components.
- **$O_{2,3}$ E:** Reviews current state of Level 2 components, and establishes corresponding links to appropriate Level 3 capabilities.
- **$O_{3,4}$ E:** Reviews current Level 3 capabilities and maps them to Level 4 tasks.
- **$O_{4,1}$ E:** Corresponds to the execution of a Level 4 task, resulting in a Level 1 interaction with the Operational Environment.

In turn, corresponding definitions for the MMF Synthesis Operators are as follows:

- **$O_{4,1}$ S:** Identifies mission tasks which would be needed to carry out particular interactions within the Operating Environment.
- **$O_{3,4}$ S:** Identifies needed Level 3 capabilities to accomplish Level 4 tasks.
- **$O_{2,3}$ S:** Identifies Level 2 components corresponding to specific Level 3 capabilities.
- **$O_{1,2}$ S:** Estimates Operational Environment interactions carried out by Level 2 components.

Beyond these constructs, the MMF provides additional Levels for expressing location and time (Level 5), environmental conditions (Level 6), and missions (Level 7) as composed by sets of Level 4 tasks. Additional details on these sections of the MMF are provided in [4, 7]. It should be noted that these additional MMF components are considered beyond the scope of this work, but are being investigated for future efforts.

Ontologies for the MMF

Work on defining ontologies for the MMF has been carried out in multiple efforts (e.g., [4, 9]) with common objectives: (1) provide formal encoding of mission structures, to enable machine interpretability; (2) provide a generalizable encoding of missions capable of being extended by a variety of kinds of domain knowledge. While initial efforts focused on modeling limited sections of MMF for the domain of Sensor-to-Mission assignment [9], more recent work [4] has defined an ontology aimed at capturing the full MMF model. In the latter effort, the goal was to provide a generalized representation of missions, in which specialized variants of the Levels and Operators could be externally defined. This modular approach towards structuring mission knowledge is now actively being considered in ISR-based systems [10], making MMF an attractive model for supplementing VoI assessment systems and knowledge bases.

3. Structuring of the Mission-VoI Ontology

The Mission-VoI ontology was designed to build upon prior efforts in mission-centric VoI representation [5, 6], as well as recent work on defining the Missions and Means Framework (MMF) ontology [4]. Mission-VoI consists of three modules, each aimed at representing different components of VoI assessments:

(1) **Mission History Record (MHR)**: Building on the MMF, the MHR encodes mission events in the form of task cycles, as defined in Section 2.2. The MHR aims to capture both histories of assets through the course of a mission, as well as records of task assignments to personnel.
(2) **User Profile**: Captures Information Object delivery preferences for a consumer, through a listing of weighting preferences for available VoI metrics.
(3) **VoI Report:** Encodes details of the VoI scoring for a particular Information Object relative to a consumer's preferences. Each VoI Report is linked to: (I) the User Profile of the target consumer; (II) the source that the Information Object was derived from.

To frame discussion of the Mission-VoI ontology, foundational definitions are given for quantitative assessment of VoI. Following this, a review of the three Mission-VoI modules will be provided.

3.1 Foundational Definition for Value of Information

This work assumes the definition of Value of Information as a quantitative value $VoI = (IO, C, M(S, W))$, where:

IO = A specific Information Object
C = A specific consumer
M = A set of VoI metrics $m_1 \ldots m_n$
S = Scorings for the VoI metrics $s_1 \ldots s_n$
W = Weightings for the VoI metrics $w_1 \ldots w_n$

From this definition, the VoI calculation for a particular Information Object and consumer can be expressed as a weighted average:

$$VoI(IO, C) = (s_1 * w_1) + (s_2 * w_2) + \ldots + (s_n * w_n)$$

Here, it is further assumed that:

- The VoI scoring is given on a scale between 0 (low value) and 1 (high value).
- All VoI metric scorings $s_1 \ldots s_n$ are given on a scale between 0 (low scoring) and 1 (high scoring).
- All VoI metric weightings $w_1 \ldots w_n$ are normalized to sum to 1.

3.2 Structuring of Mission-VoI Modules

For the three Mission-VoI modules, discussion is provided below on their structuring and features. Defined classes and properties are presented via Entity-relationship diagrams, color coded according to module membership. Components of the Mission History Record module are highlighted in BLUE, the User Profile module in GREEN, and the VoI Report module in RED.

Supplemental tables defining individual module classes and properties are provided in APPENDIX 1.

3.2.1 User Profile Module

Figure 2 diagrams the structure of the User Profile Module:

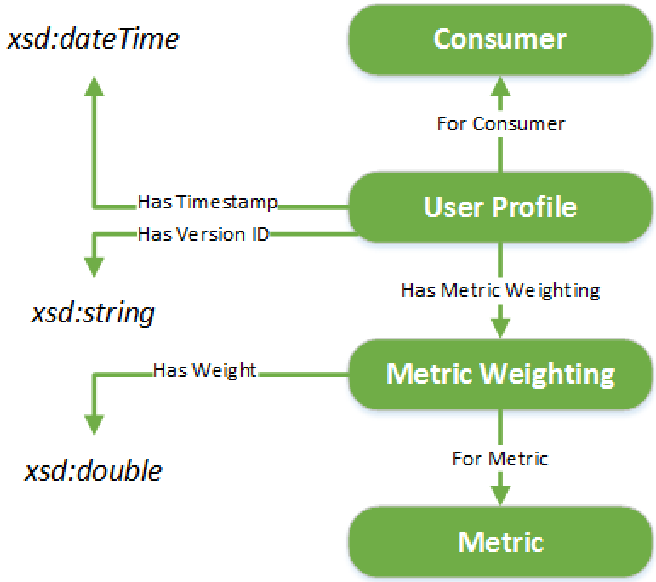

Figure 2: Class-property diagram for the User Profile Module.

The User Profile Module provides structures to represent a particular consumer's content delivery preferences, via a set of weightings for individual VoI metrics. Weightings for individual VoI metrics are given on a scale of 0 (low relevance to consumer) to 1 (high relevance).

Over time, it is assumed that consumers will adjust weightings for individual VoI metrics, resulting in different profile versions. Therefore, each User Profile instance is defined with three accompanying identifiers:

- The **consumer** that specified the profile
- The **Version ID** of the profile
- A **timestamp**, corresponding to when the profile version was generated

From an information structuring perspective, it should additionally be noted that instances of the Metric class may be linked to from multiple user profiles. This could enable, for example, comparison of weightings for a common metric across multiple profiles.

3.2.2 Mission History Record Module

Figure 3 diagrams the structure of the Mission History Record Module

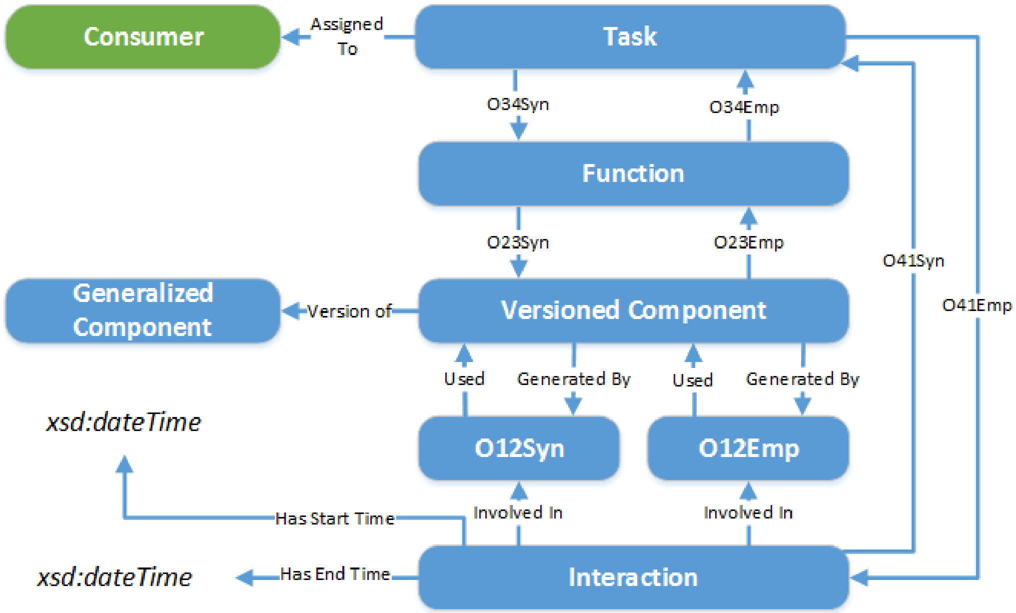

Figure 3: Class-property diagram for Mission History Record Module.

Fundamentally, the Mission History Record module builds upon definitions in the MMF ontology [4]. However, a key contribution of the Mission History Record concerns the re-definition of the MMF Level 2 component into two separate classes:

- **Versioned Component**: Representing a component at a particular point in time.
- **Generalized Component**: Represents the abstract concept of a component across time.

By definitions provided in the MMF model (Section 2.2), Level 1 interactions impact Level 2 components. To illustrate this, consider the example of an Imaging Sensor *S* at four different points in time: $\mathbf{T_0}$, $\mathbf{T_1}$, $\mathbf{T_2}$ and $\mathbf{T_3}$. Here, assume that each time $\mathbf{T_{0...3}}$ corresponds to an interaction with *S*:

- $\mathbf{T_0}$**:** S is activated by an OWNFOR technician.
- $\mathbf{T_1}$**:** Lens of S is damaged during a sandstorm.
- $\mathbf{T_2}$**:** S is repaired by an OWNFOR technician.
- $\mathbf{T_3}$**:** S is potentially tampered with. Here, OPFOR-related activity is suspected.

Under these conditions, *S* may have varying capacity to generate Information Objects at times $\mathbf{T_{0...3}}$. Hence, knowledge of the component version that produced an Information Object can be valuable in corresponding VoI calculation and assessment. To support the encoding of relationships between Interactions and Versioned Components, the Mission History Record further extends the MMF ontology by introducing the following information classes:

- **O12Syn:** Corresponds to the MMF $\mathbf{O_{1,2}}$ **S** operator, and links two Versioned Component instances to a timestamped Interaction instance.
- **O12Emp:** Corresponds to the MMF $\mathbf{O_{1,2}}$ **E** operator, and links two Versioned Component instances to a timestamped Interaction instance.

3.2.3 VoI Report Module

Figure 4 diagrams the structure of the VoI Report Module:

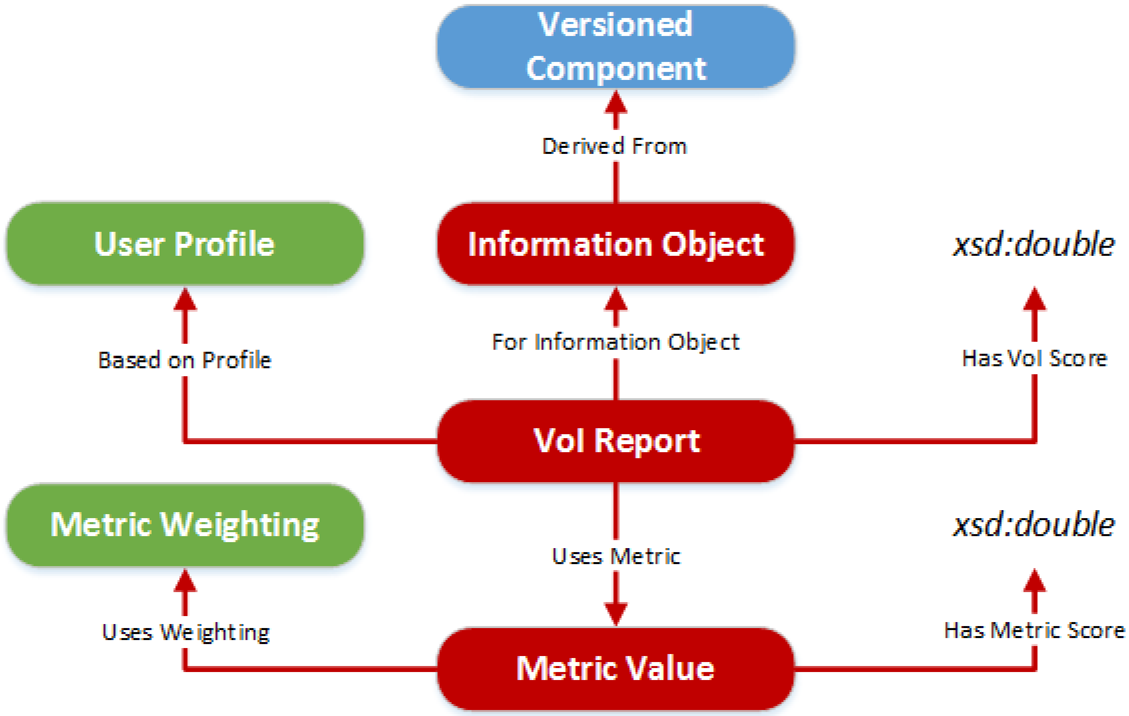

Figure 4: Class-property diagram for the VoI Report Module.

The VoI Report Module is intended to represent a VoI scoring for a particular Information Object, corresponding to a particular consumer's preferences. VoI Report instances encode the VoI score for an Information Object (as defined in Section 3.1) as well as scorings for individual VoI metrics.

As noted in Figure 5, links are made to classes defined in both the User Profile Module (User Profile, Metric Weighting) and Mission History Record Module (Versioned Component).

4. Structuring a VoI Knowledge Base

To demonstrate usage of the Mission-VoI ontology, this section provides examples of knowledge encoding for expressing mission-centric VoI assessments. These examples will be discussed in the context of a simple battlefield information retrieval scenario, aimed at highlighting the following things:

- Encoding of VoI assessments for Information Objects
- Representation of Information Objects derived across Versioned Component instances
- Variation in VoI assessments for consumers, based on User Profile content

Following discussion of the example encoding and scenario in Section 4.1, Section 4 will review a series of sample querying use cases enabled by the provided encodings.

4.1 The Scenario

In this scenario, two groups of Soldiers are tasked with managing counterinsurgency operations in an urban environment.

Mission Tasks:

For both Soldier groups, assigned mission tasks involve tracking and responding to indicators of insurgent activities, which have recently included: (I) Inciting anti-OWNFOR demonstrations; (II) Planting IEDs along roadsides; (III) Taking civilian hostages.

Sources of Information:

Across the Area of Operations, an extensive network of monitoring sensors has been deployed, which is now actively being leveraged by OWNFOR forces. These monitoring sensors were originally deployed to support civilian services, in-line with the established Smart City vision [11]. Gradually, OWNFOR-owned sensors have been deployed in-parallel with civilian sensors, resulting in a mixed-ownership network. Over time, sensors within the network have been subject to sabotage by OPFOR, vandalism by civilians, and damage due to adverse weather conditions. OWNFOR technicians have attempted to repair broken sensors when able to do so.

Monitoring the City Market:

Within the city market, an imaging sensor has regularly been taking pictures of assembled crowds to monitor for signs of hostile demonstrations. Through computational analysis, images taken from the sensor are assigned probabilities of containing demonstration-relevant events.

Recently, an increase in distortion from the imaging sensor has been observed. An OWNFOR technician was sent to repair the sensor, correcting the observed distortion. Figure 7 illustrates the generation of two images from the sensor: before the repair, and after the repair.

Content Delivery Preferences for the two Soldier Groups:

Each Soldier group has an assigned member for monitoring image feeds in the city market: John Doe (Group 1) and John Smith (Group 2).

Both Doe and Smith receive image feeds on Personal Electronic Devices, prioritized by order of VoI scoring according to their respective User Profiles (shown in Figure 7). As shown in Figure 7, both User Profiles feature different weightings for three scenario-relevant VoI metrics.

Content Delivery Outcomes:

Value of Information for images from the city market is calculated by a content dissemination service according to three metrics:

- **Presence of Demonstration:** Measures probability of demonstration activity being depicted in an image. A higher score corresponds to higher probability of demonstration activity.
- **Resolution:** Measures resolution of a captured image. A higher score corresponds to higher resolution.
- **Distortion:** Measures visual distortion in images. A higher score corresponds to lower visual distortion.

Figure 8 depicts the calculated VoI for two images from the city market for Doe and Smith, each corresponding to two versions of the same imaging sensor (as shown in Figure 6). For each VoI calculation, normalized metric weights are calculated for both Doe and Smith:

Metric	**ID**	**Weighting – Smith**	**Weighting – Doe**
Presence of Demonstration	s_1	w_1 = 0.8 / (0.8+0.8+0.4) => **.4**	w_1 = 0.9 / (0.9+0.45+0.15) => **.6**
Resolution	s_2	w_2 = 0.4 / (0.8+0.8+0.4) => **.2**	w_2 = 0.45 / (0.9+0.45+0.15) => **.3**
Distortion	s_3	w_3 = 0.8 / (0.8+0.8+0.4) => **.4**	w_3 = 0.15 / (0.9+0.45+0.15) => **.1**

Next, VoI calculations are performed of the form VoI = $(s_1 * w_1) + (s_2 * w_2) + (s_3 * w_3)$, resulting in the following VoI scorings:

	Doe	**Smith**
Image 1	(0.9*0.6) + (0.3*0.3) + (0.2*0.1) = **0.65**	(0.9*0.4) + (0.3*0.4) + (0.2*0.2) = **0.52**
Image 2	(0.45*0.6) + (0.8*0.3) + (0.5*0.1) = **0.56**	(0.45*0.4) + (0.8*0.4) + (0.5*0.2) = **0.60**

Here, Image 1 is assigned a higher VoI for Doe, while Image 2 scores higher for Smith.

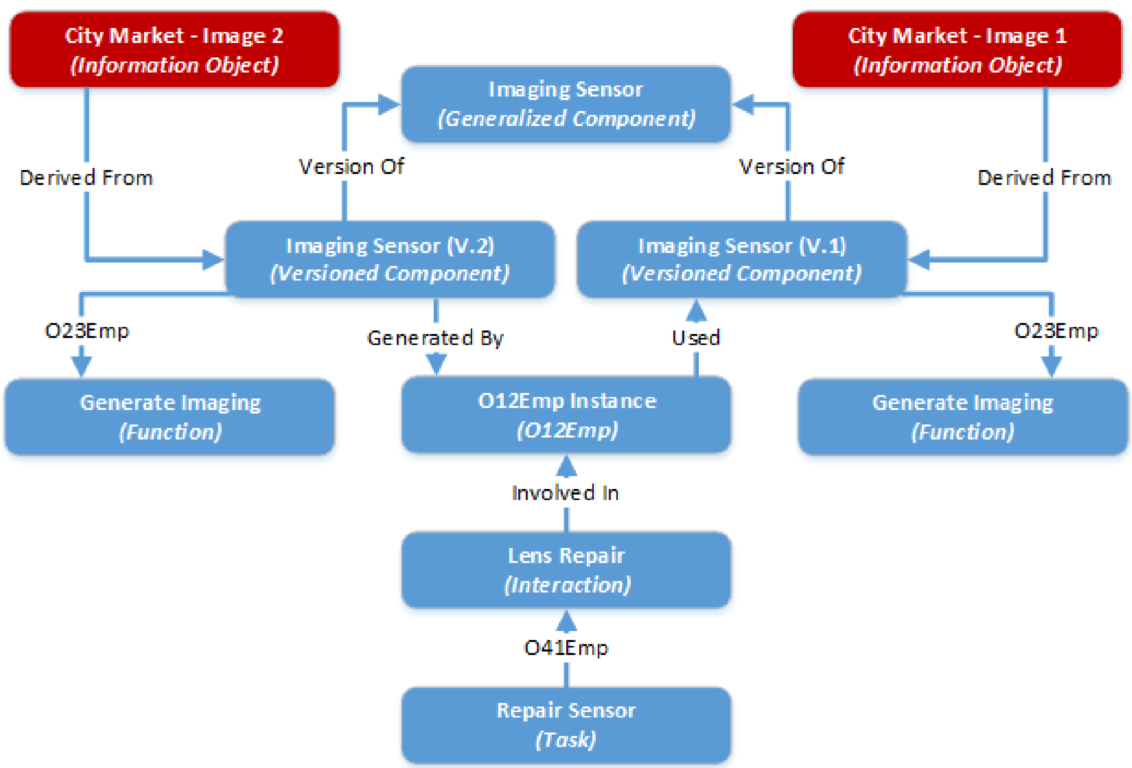

Figure 5: Encoding corresponding to generation of two images, each from the same sensor at different times.

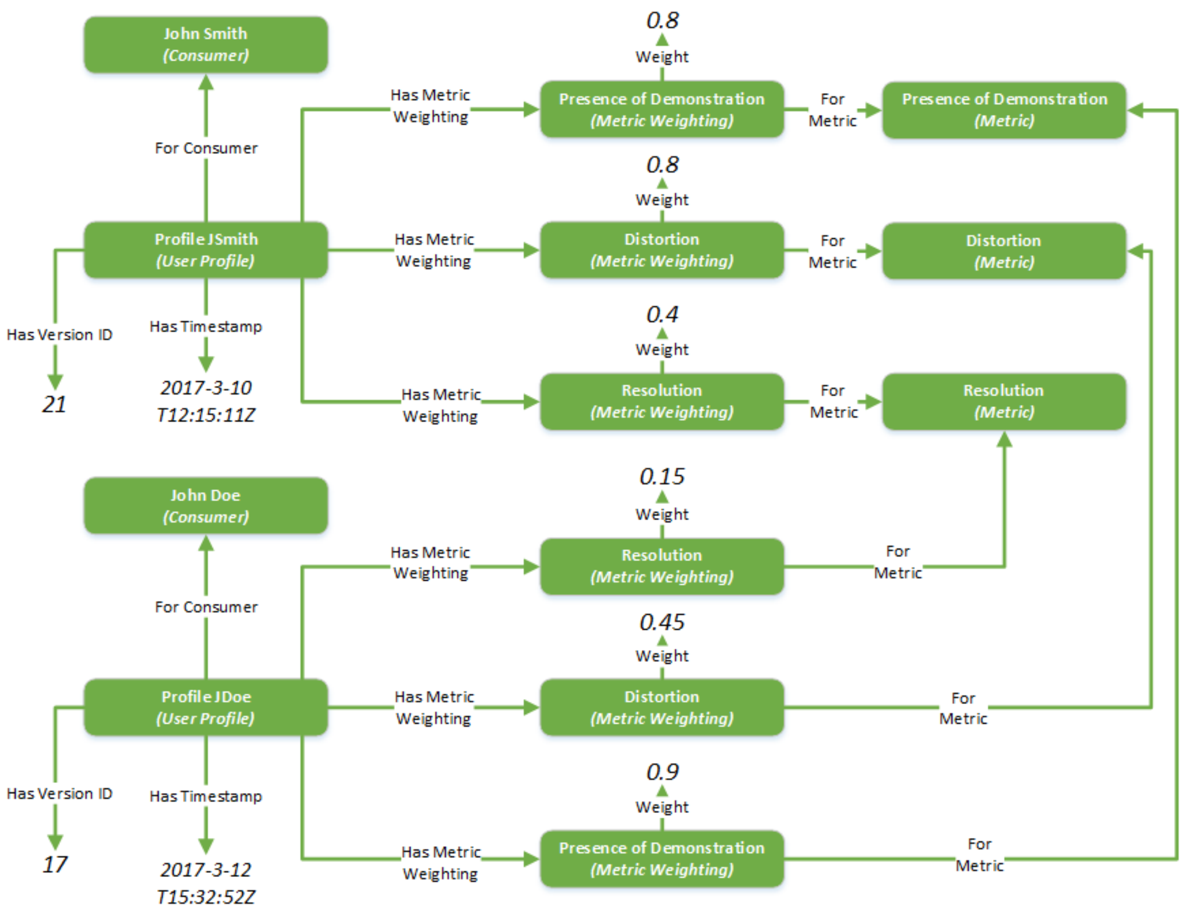

Figure 6: Encodings of User Profiles for John Smith and John Doe.

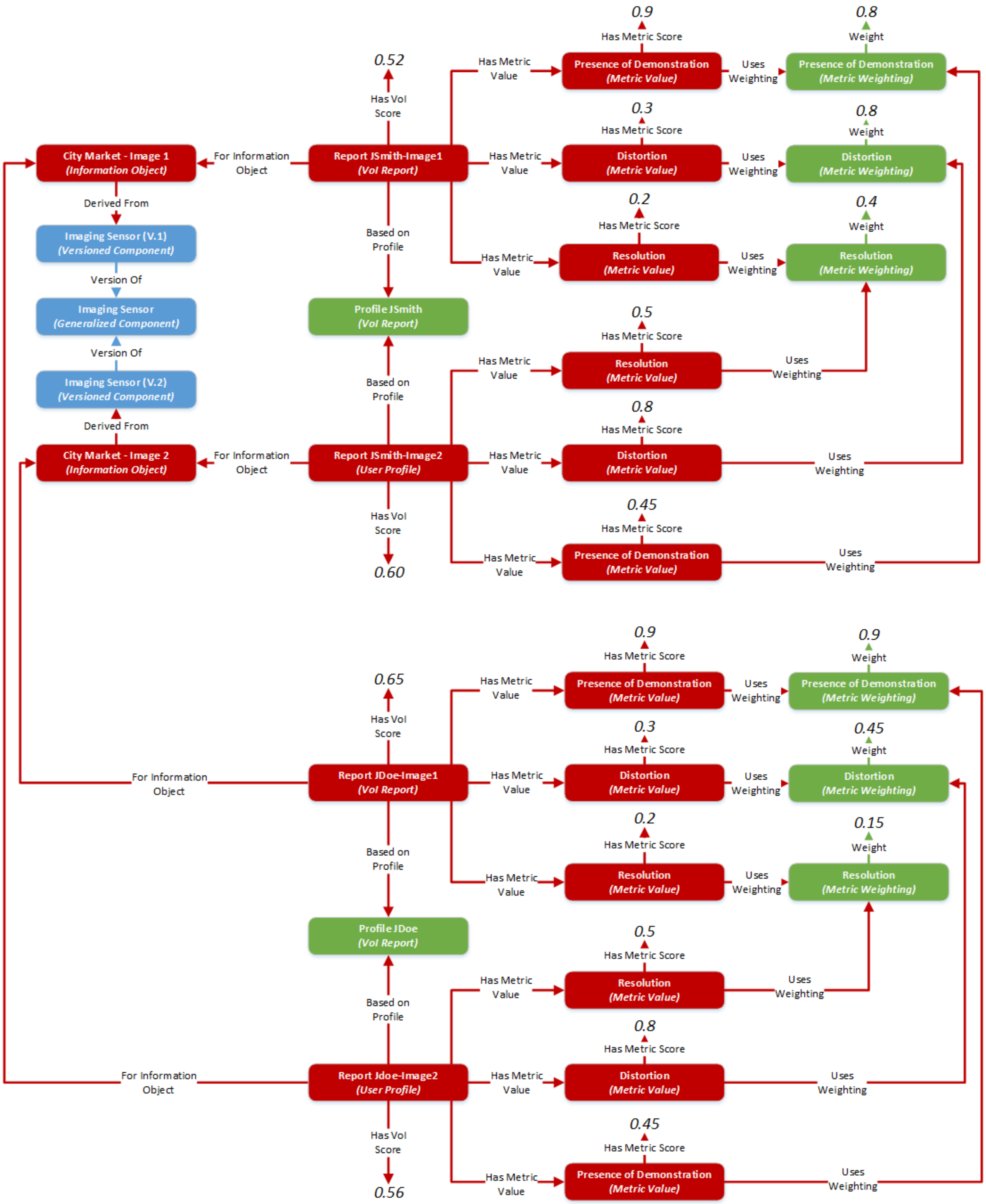

Figure 7: VoI assessment for Images 1 and 2, corresponding to the profiles of John Smith and John Doe.

4.2 Directions for Reviewing VoI Knowledge Graphs

Through Knowledge Graphs of VoI assessments based on the Mission-VoI ontology, a variety of querying and analysis use cases present themselves. Three particularly military-relevant categories of VoI assessment review are:

- **Explanation:** For one or more VoI assessments, generate an explanation to outline how the assessments were made. Here, explanations could be used to establish trust in end-results or support personnel in fine-tuning either user profiles, individual metric calculations, or which metrics are to be used in future VoI calculation.
- **Mission Narrative:** Using encoded MMF task cycles, generate an outline of past mission events tied to either the tasks of consumers or the state of components over time. This can enable generation of timeline-based mission "narratives", capable of providing additional insight on VoI assessments over a particular time period.
- **Exploration:** Based on collections of VoI Reports, along with Mission History Records and User Profiles, exploratory analysis may yield valuable insights on both the unfolding state of a battlefield, trends in content prioritization preferences given by personnel, and on trends in usage of battlefield assets.

For each of these categories, corresponding query sets can be devised based on existing graph query languages such as SPARQL [12], commonly used for RDF-encoded graph data [13]. In turn, presentation of corresponding content from the Knowledge Graph will require a suite of visualization methods, intended to highlight appropriate data relationships. Different visualization mediums may expose different insights. For example, timeline charts for presenting or mission narratives, while a mix of timeline charts and map-based visualizations could expose trends in asset usage and asset health.

5. Current Human-Information Interaction Challenges

This work is envisioned as a first step towards the development of VoI assessment systems, capable of supporting both explanation and fine-tuning of VoI assessment routines. Towards the development of future VoI analysis systems, a series of HII challenges are envisioned which stem from two areas: (i) Content selection, access and preservation strategies for VoI Knowledge Graphs; (ii) Presentation and querying strategies for content from Knowledge Graphs.

While the second area has direct impact on the end user, advances in the first area will be needed to ensure meaningful content can be made available as needed.

Towards the first area, the following challenges are envisioned:

- **Knowledge Graph Scalability:** With growth in the amount of battlefield data available, corresponding growth in the number of produced VoI assessments is to be expected. This may result in a significant scalability challenge for management of VoI assessments. Therefore, solutions must be devised to keep the number of assessments stored in Knowledge Graphs to a reasonable level.
- **Uncertainty in Mission Narratives:** The MMF represents an established model for encoding both mission planning and simulation, capable of capturing different mission events via task cycles. However, in real-world battlefields, there may be significant uncertainty regarding mission state

and events. In particular, activities carried out by OPFOR or civilian/neutral actors may not be known with certainty (rather, they may be inferred by OWNFOR observation). Therefore, methods to express uncertainty in mission narratives, and possibly use uncertainty calculations to select appropriate mission narratives for the Knowledge Graph, becomes desirable.

Towards the second area, the following challenges are envisioned:

- **Querying the KB:** Standard querying languages for both relational and graph databases commonly require both knowledge of the query language syntax and underlying data vocabularies used (e.g., schema/ontology). Since it can't be assumed users of the Knowledge Graph will be experts in either, alternative methods to enable querying must be investigated. One possibility includes Controlled Natural Language (CNL) [14, 15] which has previously been designed and evaluated for military applications.
- **Display of End-Results:** Different content from Knowledge Graphs may require different presentation modalities. Therefore, methods to promote concise display of varying forms of VoI assessment content, such as information conveyed by the Mission-VoI module set, must be investigated.

6. Conclusion

Methods for calculation of Value of Information remain an emerging research area in the domain of battlefield information management, particularly those centered on mission domain knowledge. From the perspective of Human-Information Interaction, advances in tools for VoI assessment review stand to improve personnel understanding of prioritization strategies, as well as enable fine-tuning of VoI calculation inputs (e.g., user preferences) to achieve desirable content prioritizations.

Through introduction and documentation of the Mission-VoI ontology, this work aims to provide a foundation for the development of future systems for enabling review and analysis of VoI assessment collections. From the perspective of Human-Information Interaction, advances in tools for VoI assessment review stand to improve personnel understanding of prioritization strategies, as well as enable fine-tuning of VoI calculation inputs (e.g., user preferences) to achieve desirable content prioritizations. In-line with these possibilities, future VoI-themed research is to be oriented toward addressing the challenge areas outlined in Section 5.

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APPENDIX 1 – Class / Property Tables for Mission-VoI Ontology

This section provides class and property descriptions for the Mission-VoI ontology, supplementing content provided in Section 3.

A1.1 Mission History Record Module

Class	Description
Task	Specifies individual tasks to be carried out within a mission.
Function	Expresses operational functions needed to achieve mission tasks.
Versioned Component	Represents a component version during a specific point in time.
Generalized Component	Corresponds to a component across time.
Interaction	Phenomena carried out through the execution of mission tasks, which impact the state of components. Interactions are defined to occur at specific points in time, resulting in the creation of a new Versioned Component from a previous instance.
O12Syn	Corresponds to the MMF $\mathbf{O}_{1,2}$ **S** operator, and Links 2 Versioned Component States to a timestamped Interaction.
O12Emp	Corresponds to the MMF $\mathbf{O}_{1,2}$ **E** operator, and Links 2 Versioned Component States to a timestamped Interaction.

Table 1: Class descriptions for Mission History Record Module.

Property	Domain	Range	Description
O41Syn	Interaction	Task	Corresponds to the $\mathbf{O}_{4,1}$ **S** MMF Operator.
O41Emp	Task	Interaction	Corresponds to the $\mathbf{O}_{4,1}$ **E** MMF Operator.
O34Syn	Task	Function	Corresponds to the $\mathbf{O}_{3,4}$ **S** MMF Operator.
O34Emp	Function	Task	Corresponds to the $\mathbf{O}_{3,4}$ **E** MMF Operator.
O23Syn	Function	Versioned Component	Corresponds to the $\mathbf{O}_{2,3}$ **S** MMF Operator.
O23Emp	Versioned Component	Function	Corresponds to the $\mathbf{O}_{2,3}$ **E** MMF Operator.
Used	O12Syn || O12Emp	Versioned Component	Represents the use of a Versioned Component in an $\mathbf{O}_{1,2}$ **S** or $\mathbf{O}_{1,2}$ **E** instance to derive an alternate Versioned Component.
Generated By	Versioned Component	O12Syn || O12Emp	Represents the generation of a new Versioned Component through an Interaction, captured through an $\mathbf{O}_{1,2}$ **S** or $\mathbf{O}_{1,2}$ **E** instance.
Involved In	Interaction	O12Syn || O12Emp	Links a particular interaction to an $\mathbf{O}_{1,2}$ **S** or $\mathbf{O}_{1,2}$ **E** instance.
Has Start Time	Interaction	*xsd:dateTime*	Provides a start time for the occurrence for a particular Interaction.
Has End Time	Interaction	*xsd:dateTime*	Provides an end time for the occurrence for a particular Interaction.
Version Of	Versioned Component	Generalized Component	Links a Versioned Component back to its corresponding Generalized Component
Assigned To	Task	Consumer **(User Profile)**	Links a Task to assigned personnel, represented by the Consumer class from the User Profile Module.

Table 2: Property descriptions for Mission History Record Module.

A1.2 User Profile Module

Class	Description
Consumer	Specifies the consumer tied to a particular User Profile.
User Profile	An instance of a User Profile.
Metric Weighting	A metric weighting for a VoI evaluation metric.
Metric	Represents a specific VoI evaluation metric.

Table 3: Class descriptions for User Profile Module.

Property	Domain	Range	Description
For Consumer	User Profile	Consumer	Links a User Profile instance to a particular consumer.
Has Metric Weighting	User Profile	Metric Weighting	Links a User Profile instance to a Metric Weighting.
For Metric	Metric Weighting	Metric	Specifies the VoI evaluation metric for a Metric Weighting.
Has Timestamp	User Profile	*xsd:dateTime*	Provides a timestamp for the generation of the User Profile
Has Version ID	User Profile	*xsd:string*	Provides a Version ID for the generation of the User Profile
Has Weight	Metric Weighting	*xsd:double*	Provides a numeric weighting for a particular Metric Weighting instance

Table 4: Property descriptions for User Profile Module.

A1.3 VoI Report Module

Class	Description
Information Object	Represents a specific Information Object.
VoI Report	An instance of a VoI Report.
Metric Value	Represents a scoring for an individual VoI evaluation metric.

Table 5: Class descriptions for VoI Report Module.

Property	Domain	Range	Description
Derived From	Information Object	Versioned Component **(Mission History Record)**	Links an Information Object back to its generating source.
For Information Object	VoI Report	Information Object	Specifies the Information Object a VoI Report is made for.
Uses Metric	VoI Report	Metric Value	Specifies a Metric Value applied in the VoI assessment.
Based on Profile	VoI Report	User Profile **(User Profile)**	Specifies the corresponding User Profile for generating the VoI assessment.
Has VoI Score	VoI Report	*xsd:double*	The VoI score corresponding to an Information Object and User Profile.
Uses Weighting	Metric Value	Metric Weighting **(User Profile)**	Links a Metric Value to a corresponding Metric Weighting.
Has Metric Score	Metric Value	*xsd:double*	A scoring for a VoI evaluation metric.

Table 6: Property descriptions for VoI Report Module.