DQML: A Modeling Language for Configuring Distributed Publish/Subscribe Quality of Service Policies*

Joe Hoffert, Douglas Schmidt, and Aniruddha Gokhale

Institute for Software Integrated Systems, Dept. of EECS,
Vanderbilt University, Nashville, TN, USA 37203
{jhoffert,schmidt,gokhale}@dre.vanderbilt.edu
http://www.dre.vanderbilt.edu

Abstract. Many distributed publish/subscribe (pub/sub) middleware platforms provide flexibility in configuring policies that affect end-to-end quality of service (QoS). While the functionality and tunability of pub/sub middleware has increased, so has the complexity of creating semantically compatible QoS policy configurations. This paper makes three contributions to addressing these challenges. First, it systematically analyzes three approaches for managing complex QoS policy configurations in pub/sub middleware platforms. Second, it describes how a domain-specific modeling language (DSML) can automate the analysis and synthesis of semantically compatible QoS policy configurations. Third, it empirically evaluates how this DSML increases productivity when generating valid QoS policy configurations.

Key words: Configuration Modeling Tools, Pub/Sub Middleware, Domain-Specific Modeling Languages, Data Distribution Service, Modeling Metrics

1 Introduction

Emerging trends for publish/subscribe systems. The use of distributed publish/subscribe (pub/sub) systems has increased due to their advantages of scale, cost, and performance over single computers [13, 21]. In contrast to distributed object computing middleware (*e.g.*, Java RMI and CORBA) where clients invoke point-to-point methods on distributed objects, pub/sub middleware disseminate data from suppliers to one or more consumers. Web Services Brokered Notification [19], the Java Message Service (JMS) [20], the CORBA Event Service [17], and the Data Distribution Service (DDS) [18] are examples of distributed pub/sub middleware supporting data propagation throughout a system using an anonymous subscription model that decouples event suppliers and consumers.

Distributed pub/sub middleware is applicable to a broad range of application domains, such as satellite coordination and shipboard computing environments.

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This middleware provides policies that affect end-to-end system QoS, including *persistence* (*i.e.*, saving data for current subscribers), *durability* (*i.e.*, saving data for subscribers joining at a later time), and *grouped data transfer* (*i.e.*, transmitting and receiving a group of data as a unit).

Challenges in configuring distributed publish/subscribe middleware. While tunable policies enable fine-grained control of system QoS, a number of challenges arise when developing *QoS policy configurations*, which are combinations of QoS properties that affect overall system QoS. For example, each QoS policy may have multiple parameters associated with it, such as the data topic of interest, data filter criteria, and the maximum number of messages to store when transmitting data. Each parameter can also be assigned one of a range of values (such as the legal set of topics), a range of integers for the maximum number of data messages stored for transmission, or the set of regular expressions used as filtering criteria.

The QoS policies associated with individual suppliers or consumers collectively determine the overall observed QoS of suppliers and consumers. Not all combinations of QoS policies/parameters deliver the required system QoS, however, and are thus not semantically compatible. Moreover, it can be tedious and error-prone to manually transform a valid QoS policy configuration design to its implementation in a particular middleware platform.

Solution approach → Model-driven QoS policy configuration. We have developed a domain-specific modeling language (DSML) called the *Distributed QoS Modeling Language* (DQML) to address the challenges described above. DQML helps (1) developers choose valid sets of values for QoS policies in distributed pub/sub middleware and (2) ensure that these QoS policy configurations are semantically compatible, *i.e.*, they do not conflict with each other. It also automates the transformation of a QoS policy configuration design into the correct pub/sub middleware-specific implementation.

Our prior work [9] briefly outlined some QoS policy configuration challenges and summarized our DSML-based solution approach. This paper significantly expands our prior work to (1) provide in-depth analysis of the challenges, potential solutions, and lessons learned, (2) empirically evaluate the productivity gains of our DSML solution, and (3) compare our work with related efforts.

Paper organization. The remainder of the paper is organized as follows: Section 2 describes a case study of a distributed system that can benefit from a DSML-based approach to pub/sub middleware QoS policy configuration; Section 3 highlights the challenges for QoS policy configuration for this case study and compares various approaches to addressing these challenges; Section 4 explores the structure and functionality of DQML; Section 5 empirically evaluates the productivity benefits of using DQML for configuring DDS QoS policies; Section 6 compares DQML with related work; and Section 7 presents concluding remarks.

2 Motivating Example: NASA's Magnetospheric Multiscale Mission

We chose NASA's *Magnetospheric Multiscale* (MMS) Mission as a motivating case study example to showcase the complexities of configuring QoS policies in distributed pub/sub middleware. MMS comprises five co-orbiting and coordinated satellites instrumented identically to study various aspects of the earth's magnetosphere, *e.g.*, turbulence in key boundary regions, magnetic reconnection, and charged particle acceleration. The satellites can be (re)positioned into different temporal/spatial relationships, *e.g.*, to construct a three dimensional view of the field, current, and plasma structures.

An example MMS spacecraft deployment is shown in Figure 1. This deployment includes a non-MMS satellite that can communicate with the MMS satellites, as well as a ground station with which the satellites can communicate during a high-capacity orbit window. The figure also shows the flow of data between systems involved in the deployment, along with the QoS requirements applicable to the MMS mission.

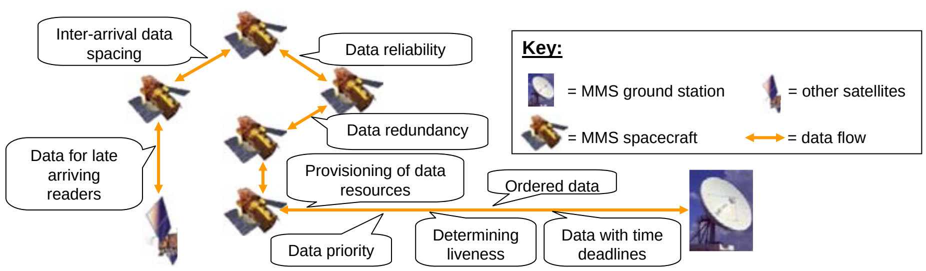

Fig. 1. Example MMS Mission Scenario with QoS Requirements

To transport telemetry data, the MMS satellites are equipped with both downlink and uplink capability. To enable precise coordination for particular types of telemetry and positioning data each satellite gathers, stores, and transmits information regarding neighboring spacecraft. Instrumentation on each satellite is expected to generate ∼250 megabytes of data per day. To enable the satellites to wait for high-rate transmission windows and thereby minimize ground station cost, each satellite also needs to store up to 2 weeks worth (*i.e.*, 3.5 GB) of data. To meet these data requirements, the distributed pub/sub middleware used for MMS would need to support the QoS policies described in Table 1.

A challenge for MMS developers is to determine what impact the interaction of the QoS policies listed above has on the deployed system. Key issues to address are determination of any conflicts of QoS settings and the behavior of the system in light of such conflicts. Not all combinations of QoS policies and parameter values are semantically compatible, *i.e.*, only a subset actually make sense and provide the needed capabilities. Ideally, developers should detect incompatibilities in QoS policy configurations *before* the system begins to run so that modifications are less costly and easier to make, validate, and optimize.

MMS Requirement	Description
Redundancy	data redundancy (store data on another satellite)
Durability	making data available at a later time for analysis
Presentation	maintain message ordering and granularity
Transport priority	prioritizing data transmissions
Time-based filtering	flow control to handle slow consumers
Deadline	deadlines on receipt of data
Reliability	no loss of critical data
Resource limits	effective provisioning of resources
Liveliness	assurances of properties when spacecraft is unavailable

Table 1. MMS pub-sub QoS Policy Requirements

3 Analyzing QoS Policy Configuration Challenges and Solutions

This section explores the challenges of generating QoS policy configurations for distributed pub/sub middleware and analyzes various solution approaches for resolving the challenges. To make the discussion concrete, we analyze it in the context of the MMS mission described in Section 2 implemented using OMG Data Distribution Service (DDS) [18] pub/sub middleware. We selected DDS as our middleware platform due to its extensive support for QoS policies.

3.1 Overview of the Data Distribution Service (DDS)

DDS is an OMG specification that defines a standard architecture for exchanging data in distributed pub/sub systems. DDS provides a logical global data store in which publishers and subscribers write and read data, respectively. DDS provides flexibility and modular structure by decoupling: (1) *location*, via anonymous publish/subscribe, (2) *redundancy*, by allowing any numbers of readers and writers, (3) *time*, by providing asynchronous, time-independent data distribution, and (4) *platform*, by supporting a platform-independent model that can be mapped to different platform-specific models, such as C++ running on VxWorks or Java running on Real-time Linux.

The DDS architecture consists of two layers. The *Data-Centric Publish Subscribe* (DCPS) layer provides efficient, scalable, predictable, and resource-aware data distribution. The *Data Local Reconstruction Layer (DLRL)* provides an object-oriented facade atop the DCPS so that applications can access object fields rather than data and defines navigable associations between objects. This paper focuses on DCPS since it is better specified and supported than the DLRL.

The DCPS entities in DDS include *topics*, which describe the type of data to be written or read, *data readers*, which subscribe to the values or instances of particular topics, and *data writers*, which publish values or instances for particular topics. Properties of these entities can be configured using combinations of the 22 DDS QoS policies shown in Table 2. Moreover, *publishers* manage groups of data writers and *subscribers* manage groups of data readers.

Each QoS policy has ∼2 parameters, with the bulk of the parameters having a large number of possible values, *e.g.*, a parameter of type long or character string. Section 3.3 shows that not all QoS policies are applicable to all DCPS entities, nor are all combinations of policy values semantically compatible.

DDS QoS Policy	Description
Deadline	Determines rate at which periodic data is refreshed
Destination Order	Sets whether data sender or receiver determines order
Durability	Determines if data outlives the time when written or read
Durability Service	Details how durable data is stored
Entity Factory	Sets enabling of DDS entities when created
Group Data	Attaches application data to publishers, subscribers
History	Sets how much data is kept to be read
Latency Budget	Sets guidelines for acceptable end-to-end delays
Lifespan	Sets time bound for "stale" data
Liveliness	Sets liveness properties of topics, data readers, data writers
Ownership	Controls writer(s) of data
Ownership Strength	Sets ownership of data
Partition	Controls logical partition of data dissemination
Presentation	Delivers data as group and/or in order
Reader Data Lifecycle	Controls data and data reader lifecycles
Reliability	Controls reliability of data transmission
Resource Limits	Controls resources used to meet requirements
Time Based Filter	Mediates exchanges between slow consumers and fast producers
Topic Data	Attaches application data to topics
Transport Priority	Sets priority of data transport
User Data	Attaches application data to DDS entities
Writer Data Lifecycle	Controls data and data writer lifecycles

Table 2. DDS QoS Policies

3.2 Evaluating Common Alternative Solution Techniques

Several alternatives exist to address the challenges of QoS policy configurations described above, including (1) *point solutions*, which iteratively modify QoS settings based on system feedback, (2) *patterns-based solutions*, which incorporate documented design expertise, and (3) *model-driven engineering (MDE) solutions*, which use DSMLs to design and validate configurations and synthesize implementations. Below we evaluate these alternatives in terms of their ability to document and realize proven QoS policy configurations robustly.

Point solutions. This approach involves the three step process of (1) making modifications to the existing system's QoS policies, (2) gathering feedback, and (3) making further modifications based on the feedback. This iterative process can be done either at (1) *run-time*, *i.e.*, while the system is executing, or (2) *development time*, *i.e.*, while the system is being developed. In either case, developers must design a proper QoS policy configuration and ensure correct configuration transformation from design to implementation.

Point solutions work best when a configuration expert is available, the configuration is simple, and the configuration need not be maintained or enhanced. Under these circumstances the problem is simplified and the overhead of training others, codifying the expertise, or otherwise developing for modifiability may not be needed.

Point solutions make it hard, however, to capture proven QoS policy configurations or leverage from the expertise of others. The configuration solutions that are designed often need the help and advice of human experts, which can create productivity bottlenecks. If there are no experts available developers must generate expertise "on-the-fly" while solving configuration problems, which is tedious and error-prone. Moreover, point solutions do not support automated transformation of configuration solutions from design to implementation.

Patterns-based solutions. In this approach *configuration patterns* are used to address QoS policy configuration challenges. The patterns document the use of QoS policies that provide shaping, prioritization, and management of a dataflow in a network [14]. For example, developers of DDS-based systems could limit access to certain data by using the *DDS Controlled Data Access* pattern, which utilizes the DDS Partition and User Data QoS Policies along with other DDS elements to provide the desired QoS.

Configuration patterns enable the codification of configuration expertise so that it is clearly documented and can be broadly reused. These patterns address the problems of human expert availability by making the configuration policy expertise generally available. However, a drawback with a patterns-based approach is the responsibility developers have for correctly transferring the configuration design into implementation manually, which can be tedious and error-prone. Moreover, various developers may implement the patterns in different ways, which can impede reuse and large-scale system integration.

DSML-based solutions. This approach to addressing the complexity of managing QoS policy configurations involves the use of DSMLs that codify configuration expertise in the metamodels developed for a particular domain. DSMLs also use an executable form of that expertise to synthesize part or all of an implementation. For example, DSMLs can generate valid QoS policy configuration files from valid QoS policy configurations modeled in the DSMLs.

DSMLs can also ensure (1) proper semantics for specifying QoS policies and (2) all parameters for a particular QoS policy are properly specified and used correctly, as described in Section 1. At design time, therefore, they can detect many types of QoS policy configuration problems, such as invalid parameter values for a QoS policy and conflicting QoS policies. They can also automate the generation of implementation artifacts (*e.g.*, source code and configuration files) that reflect design intent. Due to these benefits, this paper focuses on DSML-based solutions.

3.3 DDS QoS Policy Configuration: Challenges and DSML-based Solutions

In the context of DDS and the MMS case study, we have identified the following general DSML-based solutions to four types of challenges when creating QoS policy configurations.[2]

Challenge 1: Managing QoS Policy Configuration Variability.
Context. DDS provides three points of variability with respect to QoS policy configurations: (1) the associations between a single DDS entity and two or more QoS policies, (2) the associations between two or more entities, and (3) the number and types of parameters per QoS policy.

Problem. When creating a DDS QoS policy configuration, associations are made between various entities *e.g.*, between a data writer sending collected data

[2] Similar analysis and solutions are also applicable to other pub/sub middleware and application domains, though DDS's rich set of QoS policies makes it a particularly interesting platform.

from an MMS satellite and the publisher that manages the data writer. Not all possible associations are valid, however. For example, the association between a data writer and a subscriber is invalid since a subscriber manages one or more data readers and not data writers. If the rules governing valid associations between entities are not obeyed when associations are created the QoS policy configuration will be invalid.

Associations can be made not only between DDS entities but also between a DDS entity and the QoS policies. Not all QoS policies are valid for all DDS entities, however. For instance, associating a Presentation QoS policy with an MMS ground station's data reader is invalid. The rules that determine which QoS policies can be associated with which DDS entities must be considered when creating valid QoS policy configurations.

Finally, the number and types of parameters differ for each QoS policy type. The number of parameters for any one QoS policy ranges from one (*e.g.*, Deadline QoS Policy) to six (*e.g.*, Durability Service QoS Policy). The parameter types for any one QoS policy also differ. The parameter types include boolean, string, long, struct, and seven different types of enums. It is hard to track the number of parameters a particular QoS policy has manually; it is even harder to track the valid range of values that any one single parameter can have.

General DSML-based solution approach. A DSML can ensure that only appropriate associations are made between entities and QoS policies. In addition, a DSML can list the parameters and default values of any selected QoS policy. DSMLs ensure that only valid values are assigned to the QoS policy parameters. For example, a DSML can raise an error condition if a string is assigned to a parameter of type long. Section 4.2 describes how DQML addresses the QoS policy configuration variability challenge by allowing only valid values to be assigned to parameters and checking for valid associations between QoS policies and entities.

Challenge 2: Ensuring QoS compatibility.

Context. DDS defines constraints for compatible QoS policies. Table 3 lists the QoS policies that can be incompatible and the relevant types of entities for those policies. Incompatibility applies to QoS policies of the same type, *e.g.*, *reliability*, across multiple types of entities, *e.g.*, *data reader* and *data writer*.

QoS Policies	Affected DDS Entities	QoS Policies	Affected DDS Entities
Deadline	Topic, data reader, data writer	Liveliness	Topic, data reader, data writer
Destination Order	Topic, data reader, data writer	Ownership	Topic, data reader, data writer
Durability	Topic, data reader, data writer	Presentation	Publisher, subscriber
Latency Budget	Topic, data reader, data writer	Reliability	Topic, data reader, data writer

Table 3. Potential Incompatible DDS QoS Policies

Problem. When compatibility constraints are violated data will not flow between DDS data writers and data readers, *i.e.*, compatibility impacts topic dissemination. For example, an incompatibility between reliability QoS policies will occur if an MMS ground station requests data be sent reliably, but an MMS spacecraft only offers sending data via best-effort. The data will not flow between the spacecraft and the ground station because the values of the QoS policies are incompatible, as shown in Figure 2.

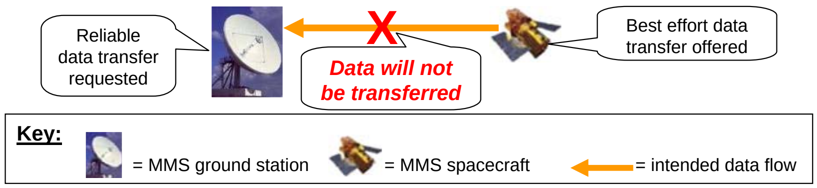

Fig. 2. Incompatible MMS Ground Station and Spacecraft Reliability QoS

General DSML-based solution approach. A DSML can include compatibility checking in the modeling language itself. A DSML user can invoke compatibility checking to make sure that the QoS policy configuration specified is valid. If QoS policies are found to be incompatible then the user is notified *at design time* and given details of the incompatibility. Section 4.2 describes how DQML addresses the QoS compatibility challenge by providing compatibility constraint checking on QoS policy configurations.

Challenge 3: Ensuring QoS consistency.

Context. The DDS specification defines when QoS policies are inconsistent, *i.e.*, when multiple QoS policies associated with a single DCPS entity are not valid. Table 4 describes the consistency constraints for QoS policies associated with a single DDS entity. For example, an inconsistency between the Deadline and

Consistency Constraints for QoS Policies
Deadline.period ≥ Time_Based_Filter.minimum separation
Resource_Limits.max_samples ≥ Resource_Limits.max_samples_per_instance
Resource_Limits.max_samples_per_instance ≥ History.depth

Table 4. DDS QoS Consistency Constraints

Time-based Filter QoS policies occurs if an MMS ground station tries to set the *Deadline* QoS policy's deadline period to 5 ms and the *Time-based Filter* QoS policy's minimum separation between incoming pieces of data to 10 ms, as shown in Figure 3. This invalid configuration violates the DDS constraint of deadline period ≥ minimum separation.

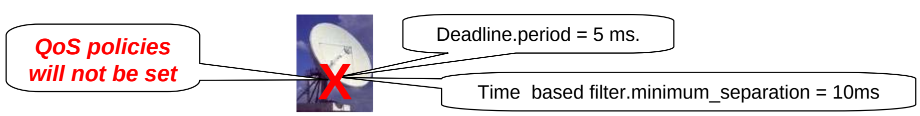

Fig. 3. Inconsistent QoS Policies for an MMS Ground Station

Problem. Manually checking for all possible consistency constraint violations is tedious and error-prone for non-trivial distributed pub/sub systems.

General DSML-based solution approach. A DSML can include consistency checking in the modeling language itself. As with compatibility checking, DSML users can invoke consistency checking to ensure that the QoS policy configuration is valid. If inconsistent QoS policies are found users are notified *at design time* with detailed information to help correct the problem. Section 4.2 describes how DQML addresses the QoS consistency challenge by providing consistency constraint checking on QoS policy configurations.

Challenge 4: Ensuring Correct QoS transformation.
Context. After a valid QoS policy configuration has been created it must be correctly transformed from design to implementation.

Problem. A conventional approach is to (1) document the desired QoS policies, parameters, values, and associated entities often in an *ad hoc* manner (*e.g.*, using handwritten notes or conversations between developers) and then (2) transcribe this information into the source code. This *ad hoc* process, however, creates opportunities for accidental complexities as the QoS policies, parameters, values, and related entities can be misread, mistyped, or misunderstood so that the QoS policy configurations that are encoded in the system differ from the valid configurations intended originally.

General DSML-based solution approach. A DSML can provide model interpreters to generate correct-by-construction[3] implementation artifacts. The interpreters iterate over the QoS policy configuration model designed in the DSML to create appropriate implementation artifacts (*e.g.*, source code, configuration files) that will correctly recreate the QoS policy configuration as designed. Section 4.2 describes how DQML addresses the challenge of correct QoS transformation by providing an interpreter which traverses the model and generates implementation specific artifacts.

4 The Distributed QoS Modeling Language (DQML)

The *Distributed QoS Modeling Language* (DQML) is a DSML that automates the analysis and synthesis of semantically compatible DDS QoS policy configurations. We developed DQML using the Generic Modeling Environment (GME) [1], which is a meta-programmable environment for creating DSMLs. This section describes the structure and functionality of DQML and details how it resolves the challenges described in Section 3.3 in the context of DDS and the MMS case study.

4.1 Structure of the DQML Metamodel

The DQML metamodel constrains the possible set of models for QoS policy configurations, as described below.

Scope. The DQML metamodel includes all DDS QoS policy types shown in Table 2, but supports only DDS entity types that have QoS policies associated with them. In addition to topics, data readers, and data writers previously mentioned, DQML can associate QoS policies with (1) *publishers*, which manage one or more data writers, (2) *subscribers*, which manage one or more data readers, (3) *domain participants*, which are factories for DDS entities for a particular

[3] In this paper "correct-by-construction" refers to QoS policy configuration artifacts that faithfully transfer design configurations into implementation and deployment.

domain or logical network, and (4) *domain participant factories*, which generate domain participants. While other entities and constructs exist in DDS, none directly use QoS policies and are thus excluded from DQML.

Figure 4 shows a portion of the DQML metamodel relevant to the Deadline QoS policy and its relationships to applicable DDS entities, *e.g.*, data reader, data writer, and topic. This figure shows the appropriate relationships and the

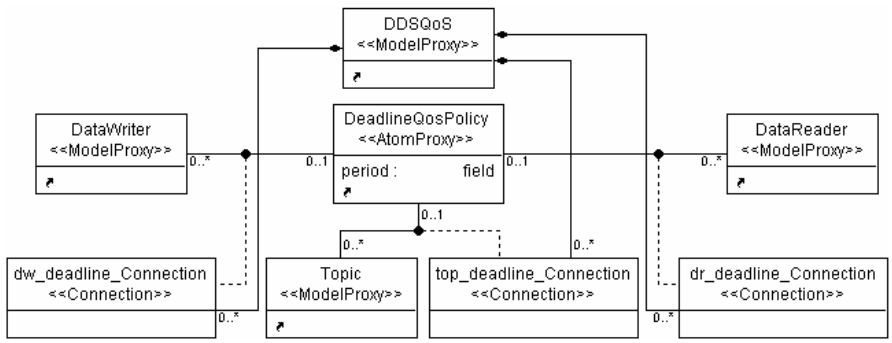

Fig. 4. Deadline QoS Policy Relationships (UML notation)

number of associations. Other QoS policies are modeled in this way, along with the parameters and constraints for each policy.

Associations between entities and QoS policies. DQML supports associations between DDS entities and QoS policies rather than having DDS entities contain or own QoS policies. This metamodel design decision allows greater flexibility and ease of constraint error resolution. If QoS policies had been contained by the DDS entities then multiple DDS entities would not be able to share a common QoS policy. Instead the policy would need to be manually copied and pasted from one entity to another, thereby incurring accidental complexity when designing a QoS policy configuration.

In contrast, DQML supports multiple DDS entities having the same QoS policy by allowing modelers to create a single QoS policy with the appropriate values. Then modelers can create associations between the applicable DDS entities and the QoS policy. This approach also eases resolution of constraint errors. In many cases, if constraint errors are found, the offending entities can be associated with a common QoS policy to eliminate the compatibility error.

Constraint definition. The DDS specification defines constraints placed on QoS policies for compatibility and consistency. The DQML metamodel uses GME's Object Constraint Language (OCL) [22] implementation to define these constraints. As noted in Section 3.3 for challenges 2 and 3, compatibility constraints involve a single type of QoS policy associated with more than one DDS entity, whereas consistency constraints involve a single DDS entity with more than one QoS policy. Both types of constraints are defined in the metamodel and can be checked when explicitly initiated by users.

To maximize flexibility, DQML does not enforce semantic compatibility constraints automatically in the metamodel since users may only want to model some parts of a DDS application, rather than model all required entities and

QoS policies. Only checking constraints when initiated by modelers enables this flexibility. Conversely, association constraints (*i.e.*, the valid associations between DDS entities and QoS policies) *are* defined in the metamodel and are thus checked automatically when associations are specified.

4.2 Functionality of DQML

DQML allows developers to designate any number of DDS entity instances involved with QoS policy configuration. For example, DQML supports the seven DDS entity types that can be associated with QoS policies, as shown in Figure 5. QoS policies can be created and associated with these entities as described below.

Fig. 5. DDS Entities Supported in DQML

Specification of QoS policies. DQML allows developers to designate the DDS QoS policies involved with a QoS policy configuration. DQML supports all DDS policies, along with their parameters, the appropriate ranges of values, and the default parameter values. Developers can then change default settings for QoS policy parameters as needed. Moreover, if a QoS policy parameter has a limited range of values, DQML enumerates only these specific values and ensures that only one of these values is assigned to the parameter.

DQML also ensures that the type of value assigned is appropriate. For example it ensures that a character value is not assigned to a parameter that requires an integer value. The DQML interpreter externalizes the parameter values (whether set explicitly or by default) so that no QoS policy has uninitialized parameters.

Figure 6 shows an example of how DQML addresses the challenge of managing QoS policy configuration variability as outlined in Section 3.3. In this example DQML displays the parameters for the history QoS policy along with the default values for the parameters in grey, *i.e.*, `history_depth = 1` and `history_kind = KEEP_LAST`. Since `history_kind` is an enumerated type, DQML lists the valid values when the user selects the parameter. Only one of the valid values can be assigned to the parameter.

Association between entities and QoS policies. DQML supports generating associations between the DDS entities themselves and between a DDS entity and the QoS policies. DQML enforces that only valid associations are created *i.e.*, where it is valid to associate two particular types of entities or associate a particular DDS entity with a particular type of QoS policy. DQML will notify developers if the association is invalid and disallow the association at design-time.

Checking compatibility and consistency constraints. DQML supports checking for compatible and consistent QoS policy configurations. The user initiates this checking and DQML reports if there are any violations. Constraint

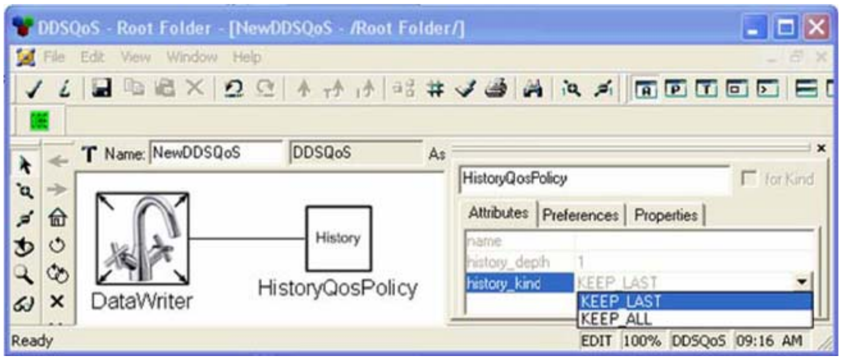

Fig. 6. Example of DQML QoS Policy Variability Management

checking in DQML uses default QoS parameter values to determine QoS compatibility and consistency if no values are specified. Developers of QoS policy configurations might explicitly associate only a single QoS policy to an entity and assume no checking for compatibility or consistency is applicable. A constraint violation may exist, however, depending on the interaction of the explicit parameter values and the default values for other entities.

For instance, if developers specify only a single presentation QoS policy in a configuration, associate it with a single subscriber entity, and change the default *access scope* value from *instance* to *topic* or *group*, they may assume no constraint violations occur. The explicit access scope value set on the subscriber is incompatible, however, with the implicit (default) value of *instance* for *any* publisher associated via a common topic.

The constraint resolution problem is further exacerbated by QoS policies that can be associated with a topic entity and then act as the default QoS policy for data readers or writers. For example, the reliability QoS policy can be associated with a data reader, a data writer, or a topic. If the policy is associated with a topic, any data readers or data writers not explicitly associated with a reliability policy will use the topic's reliability QoS policy. DQML can check this type of QoS association for compatibility and consistency.

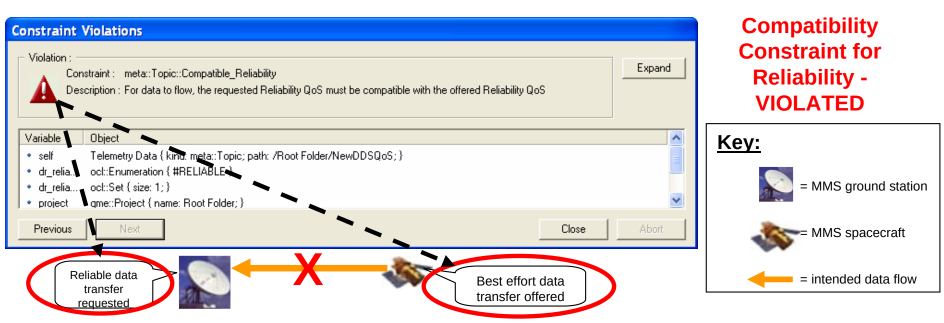

Fig. 7. Example of DQML QoS Policy Compatibility Constraint Checking

Figures 7 and 8 show examples of how DQML addresses the challenges of ensuring QoS compatibility and consistency, respectively, as described in Section 3.3. Figure 7 shows how DQML detects and notifies users of incompatible

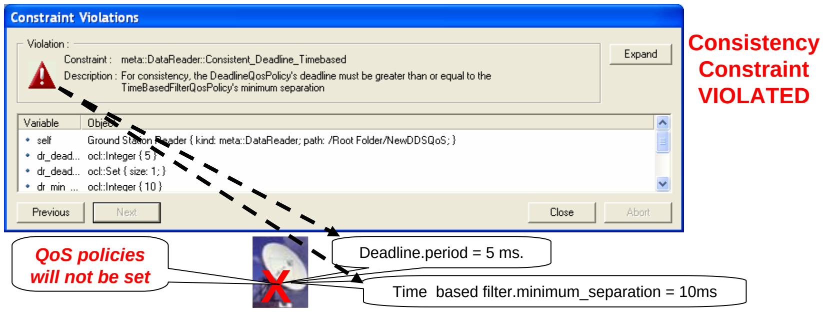

Fig. 8. Example of DQML QoS Policy Consistency Constraint Checking

reliability QoS policies. Likewise, Figure 8 shows an incompatible deadline period, *i.e.*, 10 is less than the time based filter's minimum separation of 15. Both policies are associated with the same MMS Ground Station data reader. DQML checks the consistency of the modeled QoS policies and notifies users of violations.

Transforming QoS policy configurations from design to implementation. Figure 9 shows how DQML addresses the challenge of correctly transforming QoS policy configurations from design to implementation, as described in Section 3.3. In this example, DQML generates a QoS policy configuration file for an MMS satellite data reader. QoS policies associated with the data reader along with values for the policies are shown. This file can then be integrated into the MMS implementation to ensure the desired QoS policy configuration.

```
datareader.deadline.period=10
datareader.durability.kind=VOLATILE
datareader.liveliness.lease_duration=10
datareader.liveliness.kind=AUTOMATIC
datareader.reliability.kind=BEST_EFFORT
datareader.reliability.max_blocking_time=100
datareader.resource_limits.max_samples=-1
datareader.resource_limits.max_samples_per_instance=-1
datareader.resource_limits.max_instances=-1
datareader.timebased_filter.min_separation=0
```

Fig. 9. Example QoS Policy Configuration File

5 Productivity Analysis of DQML for the DDS Benchmarking Environment

This section presents the results of a productivity analysis using DQML. The MMS scenario described in Figure 1 is used within the context of the DDS Benchmarking Environment (DBE) described in Sidebar 1 to evaluate MMS scenario QoS behavior. We present the productivity benefit and the break-even point of using DQML vs. manually implementing QoS policy configurations for DBE. Manual implementation of configurations is applicable to both the point and patterns-based solutions presented in Section 3.2 since neither approach provides implementation guidance.

Sidebar 1: DDS Benchmarking Environment (DBE)

DBE is a suite of software tools used to examine and evaluate various DDS implementations [10]. DBE requires correct QoS policy settings so that data will flow as expected. If these policy settings are inconsistent QoS evaluations will not commence properly. DBE runs a set of Perl scripts that launches executables for the DDS application and in particular deploys data readers and data writers onto specified nodes. For each data reader and data writer DBE also deploys a QoS policy settings file. The files and settings are currently generated manually.

5.1 The DQML DBE Interpreter

To support DBE and its need to generate correct QoS policy configurations we developed a DQML interpreter that generates QoS policy parameter settings files for the data readers and data writers that DBE configures and deploys. This interpreter can also accommodate other DCPS entities, *e.g.*, topics, publishers, and subscribers. All QoS policies from a DQML model are output for the data readers and data writers.

The DQML interpreter creates one QoS policy parameter settings file for each data reader or data writer that is modeled. The names of the files are generated by using the name of the data reader or data writer prepended with the either "DR" or "DW" plus the current count of data readers or data writers processed (*e.g.*, `DR1_Satellite1.txt`). The filename prefix is generated to ensure that a unique filename is created since the names of the data readers and data writers modeled in DQML need not be unique.

A common DBE use-case for DQML thus becomes (1) model the desired DCPS entities and QoS policies in DQML, (2) invoke the DBE interpreter to generate the appropriate QoS settings files, and (3) execute DBE to deploy data readers and data writers using the generated QoS settings files.

5.2 Productivity Analysis

Scope. DBE currently deals only with DDS data readers and data writers. Our productivity analysis therefore focuses on the QoS parameters relevant to data readers and data writers. (Similar analysis can be done for other types of DDS entities associated with QoS policies.) At a minimum, in the MMS scenario each MMS satellite, non-MMS satellite, and ground station will have a data writer and data reader to send and receive data, respectively, which yields seven data readers and seven data writers to configure. This scenario provides the minimal baseline since production satellites and ground stations typically have many data writers and data readers for use in sending and receiving not only to other systems but also for use internally between various subsystems.

A data writer can be associated with 15 QoS policies with a total of 25 parameters, as shown in Table 5. A data reader can be associated with 12 QoS

QoS Policy	# of Params	Param Type(s)
Deadline	1	int
Destination Order	1	enum
Durability	1	enum
Durability Service	6	5 ints, 1 enum
History	2	1 enum, 1 int
Latency budget	1	int
Lifespan	1	int
Liveliness	2	1 enum, 1 int
Ownership	1	enum
Ownership Strength	1	int
Reliability	2	1 enum, 1 int
Resource Limits	3	3 ints
Transport Priority	1	int
User Data	1	string
Writer Data Lifecycle	1	bool
Total Parameters	**25**	

Table 5. DDS QoS Policies for data writers

QoS Policy	# of Params	Param Type(s)
Deadline	1	int
Destination Order	1	enum
Durability	1	enum
History	2	1 enum, 1 int
Latency budget	1	int
Liveliness	2	1 enum, 1 int
Ownership	1	enum
Reader Data Lifecycle	1	int
Reliability	2	1 enum, 1 int
Resource Limits	3	3 ints
Time Based Filter	1	int
User Data	1	string
Total Parameters	**17**	

Table 6. DDS QoS Policies for data readers

policies with a total of 17 parameters, as shown in Table 6. The total number of relevant QoS parameters for DBE is thus **17 + 25 = 42**. Each QoS parameter value for a data reader or writer corresponds to one line in the QoS policy parameter settings file for DBE, as shown in Figure 9.

Interpreter development. DQML's DBE interpreter was developed using GME's Builder Object Network (BON2) framework, which generates C++ code using the Visitor pattern [6]. Within BON2, developers of the DQML DBE interpreter need only modify and add certain portions to the framework that are called to process the particular DSML. The DQML-specific code for the DBE interpreter contains 160 C++ statements that were developed specifically for DQML and DBE.

The C++ development effort for the DBE interpreter need only occur once. In particular, no QoS policy configuration for DBE incurs this development overhead since the interpreter already exists. The development effort is included *only* for comparison with manually implemented QoS policy configurations.

The interpreter code is fairly straightforward once developers understand how to navigate the model in the BON2 framework and access the appropriate information. Although developers should be familiar with the Visitor pattern (since the BON2 framework uses it heavily), they only need define the appropriate methods for the automatically generated Visitor subclass. In general, the DQML interpreter code specific to DBE gathers model information, creates the QoS settings files, and outputs the settings into the QoS settings files.

The most challenging part of developing DQML's DBE interpreter is navigating through the model's QoS policy elements and related entities using the BON2 framework. Conversely, the most challenging aspects of handcrafting QoS policy configurations are (1) maintaining a global view of the model to ensure compatibility and consistency and (2) remembering the number of and valid values for the parameters of the various QoS policies. For non-trivial QoS policy configurations, therefore, developing the DQML-specific C++ code for the interpreter is no more complex than manually ensuring that the QoS settings in settings files are valid, consistent, compatible, and correctly represent the designed configuration.

Analysis for the MMS scenario. As a conservative approximation, the creation and use of the DBE interpreter for DQML has its break-even point for a *single* QoS policy configuration when there are at least 160 QoS policy parameter settings needed, which correlates to the 160 C++ statements for DQML's DBE interpreter. As shown in Figure 10, using the results for QoS parameters in Tables 5 and 6 for data readers and data writers, the break-even point equates to ∼10 data readers, ∼7 data writers, or some combination of data readers and data writers where the QoS settings are greater than or equal to 160 (*e.g.*, 5 data readers and 3 data writers = 160 QoS policy parameter settings).

From the analysis above—and using the minimal MMS scenario in Figure 1 of 7 data writers and 7 data readers—the total number of QoS parameters to consider is 7 * 25 (for data writers) + 7 * 17 (for data readers) = 294. This number exceeds the 160 lines of C++ code developed for the DBE interpreter and shows that the minimal MMS scenario warrants the use of DQML and the creation and use of the DBE interpreter.

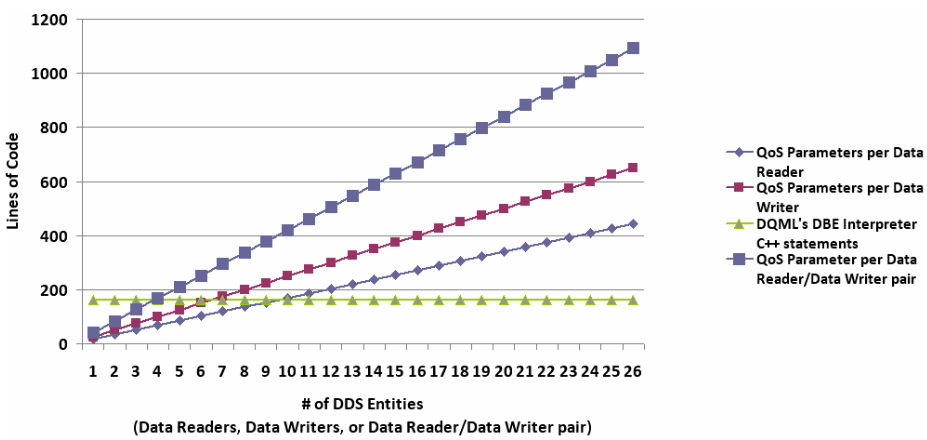

Fig. 10. Metrics for Manual Configuration vs. DQML's Interpreter

Generalized analysis. The break-even analysis above is relevant to generating a single QoS policy configuration. The analysis does not consider any subsequent modifications to an existing configuration or development of new configurations for DBE that would not require any modifications to interpreter code. Changes made to a configuration also require that developers (1) maintain a global view of the model to ensure compatibility and consistency and (2) remember the number of, and valid values for, parameters of the various QoS policies being modified. These challenges still exist when changing an already valid QoS policy configuration.

Moreover, there may be thousands of data readers and writers in large-scale DDS systems, *e.g.*, shipboard computing or air-traffic management environments [5]. Assuming 1,000 data readers and 1,000 data writers, the number of QoS parameters to manage is **17 * 1000 + 25 * 1000 = 42,000**. This number does not include QoS parameter settings for other DDS entities such as publishers, subscribers, and topics. For such large-scale DDS systems the development cost of the DQML interpreter in terms of lines of code is amortized by more than 200 times (*i.e.*, 42,000 / 160 = 262.5).

6 Related Work

This section compares our work on DQML with related R&D efforts.

DSMLs for configuring QoS. There are currently several DSMLs developed to model QoS requirements for distributed real-time embedded (DRE) systems. The *Distributed QoS Modeling Environment* (DQME) [8] is a modeling tool that targets essential elements of dynamic QoS adaptation. DQME is a hybrid of domain-specific modeling and run-time QoS adaption methods, with emphasis on adapting QoS to changing conditions with limited system resources. In contrast, DQML focuses on designing and generating correct QoS policy configurations for data-centric pub/sub middleware, such as DDS.

The *Options Configuration Modeling Language* (OCML) [3] is a DSML that aids developers in setting compatible *component* configuration options for the system being developed whereas DQML models QoS policy configuration for data-centric middleware that can be applicable across *various endpoints* such as processes, objects, or components. OCML is a modeling language intended to be domain-independent that captures complex DRE middleware and application configuration information along with QoS requirements. It is part of the Component Synthesis using Model Integrated Computing (CoSMIC) [12] tool chain. It currently supports configuration management only for distributed object computing (DOC) architectures rather than data-centric publish-subscribe architectures such as DDS. This is an important difference because the endpoints receiving data in a system utilizing DDS do not specify details of the type and implementation characteristics of the end points. For instance, these endpoints could be processes, objects, or components. DQML models QoS policy configuration for data-centric middleware that can be applicable across these various endpoints. Conversely, OCML is focused to aid developers set component configuration options for the system being developed.

The MicroQoSCORBA [4] middleware for embedded systems includes a GUI-based tool that helps guide the developer with configuration options and provides semantic compatibility for resource constrained environments. More specifically, for each of the various QoS policies allowed, *i.e.*, fault tolerance, security, and timeliness, MicroQoSCORBA supports multiple implementations that enforce any single QoS policy. These implementations are needed to offer different trade-offs between QoS and resource consumption which is often crucial for embedded systems. Additionally, an implementation for enforcing one QoS policy may not be compatible with an implementation for supporting a different QoS policy due to resource constraints for the particular hardware platform. The configuration tool guides the developer through reconciling these incompatibilities to ensure the desired balance between QoS and resource consumption. While the configuration tool helps to address the QoS needs of resource-constrained environments, it is targeted to distributed object computing middleware rather than pub/sub middleware.

Runtime monitoring. Real-time Innovations Inc. (`www.rti.com`) and Prism Technologies (`www.prismtechnologies.com`) have developed DDS products along with MDE tools that monitor and analyze the flow of data within a system using DDS. These tools help verify that a system is functioning as designed for a particular QoS policy configuration and for a particular point of execution. Discovering configuration problems at run-time is very late in the development cycle, when problems are more expensive and obtrusive to fix. Moreover, these tools are designed only for the vendor-specific DDS implementation.

In contrast, DQML allows QoS policy designers to create semantically compatible QoS policies at design time. DQML can also use the QoS policy configuration model to construct semantically compatible and syntactically correct implementation artifacts (*e.g.*, source code, configuration files) that can be incorporated into the system implementation without human intervention. Moreover, DQML is not DDS implementation specific but is more generally applicable.

Content-based pub/sub development. Tools such as Siena [2] and the Publish/subscribe Applied to Distributed REsource Scheduling (PADRES) [16] system provide support for flexible and efficient content-based subscription. PADRES is used for composite event detection and in this vein includes support for expressing time along with bindings for variables, coordination patterns, and composite subscriptions. Siena provides scalability to large content-based networks while minimizing missed deliveries and unnecessary traffic. In contrast to PADRES and Siena, DQML supports correct QoS policy configurations at design-time rather than managing dynamic content-based subscriptions during run-time.

7 Concluding Remarks

DQML is a DSML that addresses the challenges of (1) managing QoS policy configuration variability, (2) developing semantically compatible configurations, and (3) correctly transforming QoS policy configurations from design to implementation. The following lessons learned summarize our experience using DQML to model QoS policy configurations for DDS in the context of the MMS mission.

• **Ensuring the validity of QoS policy configurations is crucial to proper deployment of systems built using distributed pub/sub middleware.** As the complexity of QoS policy configuration increases, the QoS policy compatibility capabilities provided by DQML are vital for managing this complexity. When QoS policy configurations are invalid data will not be transferred properly. DQML simplifies and automates checking the validity of QoS policy configurations.

• **Ensuring that the design QoS policy configuration is the deployed configuration is crucial to system integrity.** If a valid QoS policy configuration is not transformed correctly during system deployment, the behavior of the system will be unpredictable. DQML provides model interpreters that generate implementation and deployment artifacts, *e.g.*, QoS policy configuration files, that correctly transform the QoS policies as designed.

• **OCL is complicated to learn and easy to misuse.** Many application developers are not familiar with rule-based constraint languages, such as OCL. Moreover, tool support for OCL is often rudimentary, *e.g.*, limited debugging support, which impedes productivity. In future work we plan to address enforcing constraints by evaluating other constraint solving technologies, such as the Constraint Logic Programming Finite Domain (CLP(FD)) solver [15].

• **DSMLs should build upon pattern knowledge.** A DSML can benefit from the knowledge already documented in configuration patterns by incorporating these patterns into the DSML itself. This approach ensures that different types of patterns provide semantic compatibility and are implemented correctly. We are therefore enhancing DQML to support patterns and higher level services (*e.g.*, security and fault tolerance [11]).

• **Run-time feedback provides crucial system performance insight.** While DQML ensures valid QoS policy configurations, some system properties (*e.g.*, latency and CPU resource utilization) are best evaluated at run-time. Incorporating this type of dynamic information back into a QoS policy configuration model helps increase overall development productivity and system robustness. We are evaluating ways to incorporate runtime and emulation feedback [7] into DQML to enhance QoS policy configuration development.

GME can be downloaded from `www.isis.vanderbilt.edu/Projects/gme`. DQML is part of the CoSMIC tool chain and can be downloaded in GME's XML format from `www.dre.vanderbilt.edu/~jhoffert/DQML/DDSQoS.xme`.

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