Restructuring Requirements Specifications for Managing Inconsistency and Change: A Case Study

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Abstract

This paper describes our experiences in *restructuring* multi-perspective requirements specifications in order to identify and analyse inconsistencies and manage change. A partial, heterogeneous and reasonably large requirements specification from a NASA project was analysed and decomposed into a structure of "viewpoints", where each viewpoint encapsulates partial requirements of some system components described in the specification. Relationships between viewpoints were identified which included not only the interactions explicitly stated in the requirements but also some implicit and potentially problematic inter-dependencies. The restructuring process and a first informal analysis of the resulting relationships enabled the detection of inconsistencies and the definition of some interesting *domain-dependent* consistency rules. We believe that this restructuring into viewpoints also facilitated requirements understanding through partitioning, and requirements maintenance and evolution through explicit identification of the inter-viewpoint relationships.

1 Introduction

The requirements engineering process of large and complex systems often involves the participation of many developers who operate according to their specific skills, experience and knowledge. This is particularly the case for the elicitation and development of requirements specifications. Multiple participants are normally involved in specifying different partial requirements of the same underlying system. Inevitably, these requirements are more appropriately described using various development methods and diverse representation schemes, reflecting the different knowledge and *perspectives* that the developers have about the underlying domain. Forced integration into a single uniform specification is difficult and can obscure individual views and inconsistencies. On the other hand, relationships between the various partial specification fragments, such as overlaps and inter-dependencies, are difficult to identify making consistency checking and inconsistency handling difficult as well.

To address the above problem we advocate an analysis, *a priori*, of the relationships between the methods and representation styles used to develop specification fragments [9], as well as relationships between domain-specific terms and concepts (e.g., identifying different terms which denote the same object) [3]. The aim is to preserve the individual views, to support the development method and representation scheme appropriate for each view, and to make explicit the relationships between these views.

However, given that it is not always feasible to develop, *a priori*, multi-perspective specifications with a structure amenable to analysis and management, an approach that facilitates *restructuring* of *existing* specifications seems appropriate. The approach described in this paper restructures existing informal requirement specifications, *enriching* them by identifying and explicitly representing interactions and relationships between different parts of the requirements, so facilitating consistency checking, validation, and subsequent evolutionary change.

Specifically, this paper describes our practical experiences in restructuring a partial, reasonably large, multi-perspective requirements specification taken from NASA's *International Space Station* (ISS) project. We deploy the Viewpoints framework [5, 9] as a restructuring tool. This framework facilitates an explicit separation of the perspectives of different developers and their representation by "ViewPoints"[1], allowing the use of different development methods and representation schemes. Inter-viewpoint rules are defined to provide a means for structural integration of different specification fragments, a means for consistency checking and inconsistency analysis, and a means for facilitating change management.

Our case study is an informal, but structured, partial requirements specification of an integrated hardware and software system (C&DH), which is part of a wider system for handling the operation of an earth-orbiting space station. We focus our attention on a particular function of the C&DH, namely, the "Fault, Detection, Isolation and Recovery" (FDIR) function. We illustrate how the informal specification was restructured into related viewpoints, and identify some inconsistencies revealed by this process. We also examine three other different chronological versions of the same specification to illustrate the suitability of our approach for tracking evolutionary changes and assessing their impact on the consistency of the specification.

The approach which we describe in this paper is a departure from the "traditional" way in which viewpoints have been deployed in the past. Thus, while the case study serves to validate the useability of viewpoints in a practical

[1]In this paper, we write the term "viewpoint" in lower case throughout, even though we are still referring to our particular form of "ViewPoints" described in earlier work [5, 9].

setting, it also illustrates the benefits of using them to "reverse engineer" a multi-perspective structure, given a monolithic specification. More generally, we believe that our restructuring of the original specification made it more accessible, aiding our own understanding of the underlying domain. The identification and representation of *implicit relationships* between various parts of the specifications also revealed inconsistencies that would have been difficult to detect by other means.

The paper is structured as follows. Section 2 describes the background to our approach including a summary of multi-perspective software development using viewpoints [5, 9] and a brief overview of our viewpoint-based restructuring approach. In Section 3, we describe the application of our approach to the case study, describe some inconsistencies that were revealed by our approach, and discuss the way in which our restructuring facilitates change management. In Section 4 we present and discuss the lessons learned from this experience. Section 5 compares our approach to related work, while Section 6 summarises our conclusions and future plans to support improved inconsistency analysis, requirements traceability, and inconsistency handling.

2 Background

The basic principle underlying the viewpoints framework is separation of concerns. Viewpoints are loosely coupled, locally managed, distributable objects that encapsulate partial representation knowledge (a notation), development knowledge (a process) and specification knowledge (a view) [5]. From a methodological standpoint, a viewpoint's notation and process are reusable attributes, and are called a viewpoint *template* (a viewpoint "type" or development "technique"). Thus, viewpoints are *instantiations* of templates, which capture some partial specification, represented in a particular notation and developed by following a particular process. *In-viewpoint* rules for each viewpoint define its semantics, requirements for well-formedness, and internal consistency.

The key to successful (and meaningful) deployment of multiple viewpoints in any software development setting, is an understanding and subsequent expression of *inter-viewpoint* relationships that define inter-dependencies and overlaps between viewpoints. Such relationships may be between the templates from which viewpoints are instantiated (e.g., syntactic relationships between constructs of different viewpoint notations) [2, 9], or specification domain-dependent relationships that (usually) emerge as development proceeds [3]. These relationships are fundamental elements of any viewpoints' structure that results from a multi-perspective development process. They provide the structural integration "glue" that holds a multi-perspective specification together, and are the only means by which consistency and completeness are meaningful in the viewpoints framework.

Some inter-viewpoint relationships are definable before development begins. This, of course, is not always the case. In a requirements engineering context, relationships between different requirements emerge as further requirements are elicited and analysed. With this in mind, we adapted the viewpoint-oriented development approach in order to examine its suitability for handling requirements specifications which are (1) not originally structured as a multi-perspective specification, and (2) still evolving.

The basic approach Our restructuring approach is situated in the middle ground between informal (and error prone) specification inspection [7] and (expensive) formal analysis [10]. Our objective is to describe existing specifications as a structure of related viewpoints, and then use this as the basis for conducting a series of consistency checks and inconsistency analyses.

The approach is comprised of five activities. Existing informal specifications are *decomposed* into parts, with each part *represented* using some notation within a viewpoint. The viewpoints' structure is then *enriched* by identifying and explicitly defining in-viewpoint and inter-viewpoint rules that express the consistency relationships within and between viewpoints. An *analysis* of this new structure is then used to validate the specification and check its consistency. The results of the analysis are then used to determine the inconsistency *handling* process and to support change management.

3 Case Study

Our case study was based on a partial, multi-perspective requirements specification of the fault protection software of NASA's International Space Station (ISS) project. This is an international co-operative programme for the construction and use of a space station orbiting earth. One of the main functions of the space station software is the *Command and Control* (C&C) function. This is responsible for the station operations by monitoring its functions, overriding them when necessary, performing fault detection, and issuing commands to control the main station modes (e.g., docking with a Shuttle, re-boosting to a higher orbit, maintaining microgravity for scientific experiments). The C&C function is carried out as part of the ISS Command and Data Handling (C&DH) system. The C&DH system is comprised of a set of Computer Software Configuration Items (CSCIs) installed in a hierarchically organised set of processors (Multiplexer/Demultiplexers - MDMs) which communicate among themselves via MIL-STD-1553 buses. The main flight processor responsible for the C&C function is denoted by "C&C MDM". The CSCI within the C&C MDM is the Command and Control Software (CCS) CSCI. The C&C MDM is located at the top of the hierarchy and is the controller of the 1553 buses to the MDMs in the hierarchy tier directly below (referred to as the Bus Controller - BC). The MDMs (along with other hardware) at this next tier are designated as Remote Terminals (RTs) on the buses.

The informal requirements specifications we analysed consisted of two partial requirements documents of the C&C MDM CSCI, called *Control Bus MDM Management* (4 pages) and *1553 Bus Failure, Detection, Isolation and Recovery*

(20 pages). The former describes the management of the MDMs connected to the BC (one of these MDMs is also the C&C MDM) which includes initialisation, shutdown and *failure recovery*. The last of these specifies the management of the control buses – e.g., detecting which of the 1553 bus channels have communication failures. Both these specifications are mainly written in English, and they include reference to some large tables containing information such as "Data Item Names", "Identification Numbers" and occasionally inputs and outputs of some of the functions. The document structure is composed of sections and subsections. These are mostly organised in paragraphs, and in each paragraph alternative requirements are often listed. The 1553 FDIR document also includes a flowchart describing the general C&C FDIR behaviour model.

3.1 Restructuring into viewpoints

The two requirements documents were decomposed into "high-level" viewpoints according to their section and subsection structures, and then refined into additional "lower-level" viewpoints according to their specification contents. The result of the decomposition was a functional hierarchy of viewpoints, with an increasing level of specification detail. Parent viewpoints tended to denote the main inputs and outputs of different functions, whereas leaf viewpoints tended to describe (parts of) functions in more detail.

Four main viewpoint templates were defined, called *hierarchic tree* (HT), *input output flow* (IOF), *data flow diagram* (DFD) and *state transition diagram* (STD). The HT template was used to instantiate a viewpoint describing the hierarchic functional decomposition of the specifications. The STD template was used to instantiate a viewpoint representing the state-based behaviour of the FDIR function described in the requirements specifications by a flowchart[2]. The IOF template represented functions or processes in terms of inputs and outputs, while the DFD template used a representation style similar to Tabular Collection Forms used in CORE [8] which represents functions in terms of actions, their inputs and outputs, and the inputs' sources and outputs' destinations. Part of the HT-based viewpoint is shown in Figure 1.

In Figure 1, the first and second levels below the root node reflect a section/subsection decomposition of the specification. The two documents examined, "CB MDM Management" and "1553 FDIR", were in fact themselves sections of a much larger document specifying the whole C&C MDM CSCI part of the ISS system, whereas the "Bus Channel Management" was a subsection of the 1553 FDIR section. The third level, on the other hand, reflects a function-based decomposition. "RT Failure Detection" and "BC Failure Detection" are two different functions described in the Bus Channel Management subsection and were therefore represented separately. The final level in the tree expresses a functional decomposition. Complex functions were decomposed into parts. Hence "Set Skip Bit" and "Switch to Backup RT" are two parts of the same function "RT Failure Detection".

[2]This was the only semi-formal description given in the 1553 FDIR requirements document.

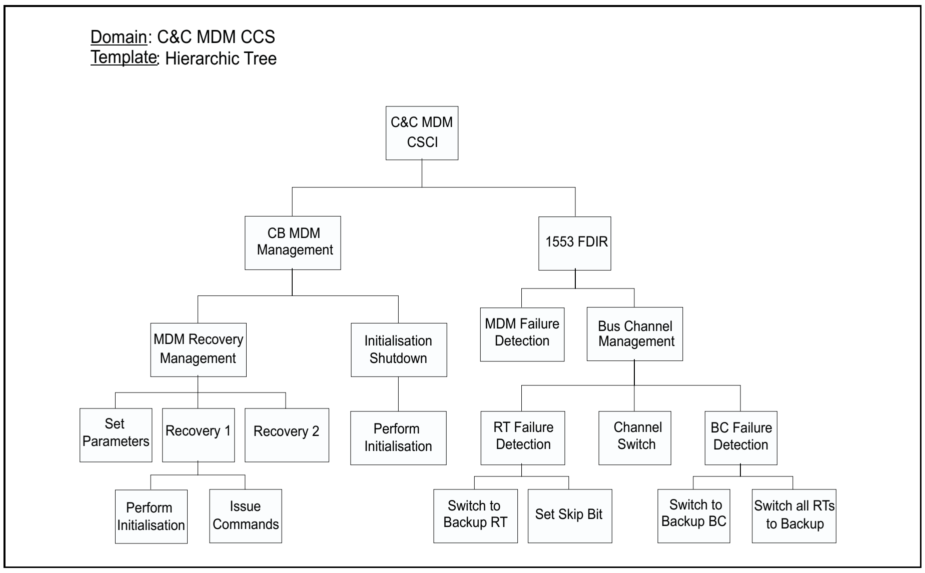


Figure 1: *Part of the hierarchical decomposition into viewpoints.*

In developing the HT template, a number of domain-independent in-viewpoint rules were defined. These expressed syntactic properties of the tree-style such as *“there is no link between nodes that are at the same level in the hierarchy”* and consistency properties within the viewpoint such as *“all nodes must have different labels”*. Structural domain-independent inter-viewpoint rules were also defined. These described the related viewpoints that should be instantiated for each node in the HT viewpoint. Some of these rules are shown in Table 1. Rules (HT1) and (HT2) defined the meaning of a “complete” restructuring of the specification – if some part identified in the hierarchical decomposition is not elaborated by some other instantiated viewpoint, then one of these rules is violated. Rules (HT3) and (HT4), on the other hand, expressed properties related to hierarchic (parent-child) relationships. (HT3) reflects the fact that for each primitive process in a (parent) IOF viewpoint, there exists in the hierarchic tree an associated lower-level (child) viewpoint which describes that process in more detail. Since the process is primitive, the total set of inputs in the IOF viewpoint should be equal to the total set of inputs in the DFD lower-level viewpoint. Finally, rule (HT4) covers the case of non-primitive processes in parent IOF viewpoints for which child lower-level viewpoints have been defined. In this case, the lower-level viewpoint specifies a further decomposition of the non-primitive process in the parent viewpoint into sub-processes, and this specification could well include additional inputs and outputs. This is illustrated by considering the IOF parent viewpoint in Figure 2 and the lower-level child viewpoint in Figure 3.

In the IOF template, functions were represented as alternative processes

Rule Name	Rule Definition
(HT1)	*For each leaf node there exists a VP instantiated from the DFD template.*
(HT2)	*For each parent node there exists a VP instantiated from either the IOF or the STD templates.*
(HT3)	*If for a node X there exists a VP A instantiated from the IOF template, then for each subnode Y, which is a primitive process in X and for which there exists a VP B instantiated from the DFD template, the set of inputs in Y is equal to the set of inputs in X.*
(HT4)	*If for a node X there exists a VP A instantiated from the IOF, template, then for each subnode Y, which is a non-primitive process in X and for which there exists a VP B instantiated either from the DFD template or from the IOF template, then the set of inputs to the process X in A is extended with the set of inputs represented in B.*

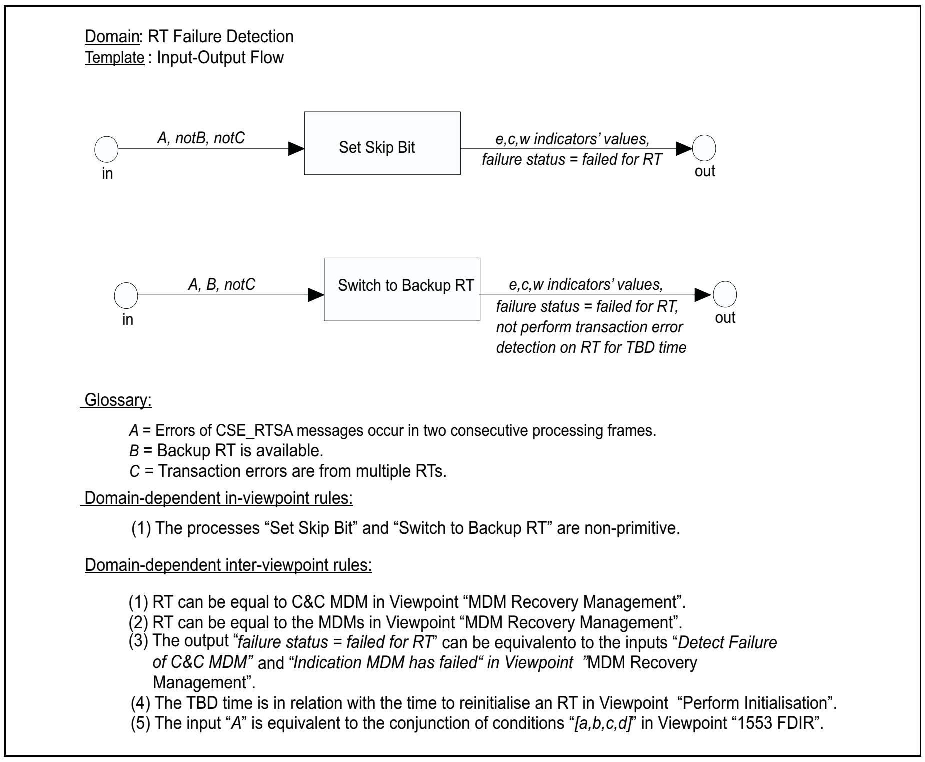
Table 1: *Inter-viewpoint rules for the HT template.*

(denoted by boxes) and inputs and outputs (denoted by arrows). Inputs can be either events (e.g., "loss of 1553 communication"), particular values of some special control parameters (e.g., "failure status = failed for RT"), or some specific commands (e.g., "Reconfigure MDM"). Similarly for the outputs. Processes can be either "non-primitive" or "primitive". Domain-dependent in-viewpoint rules specify the processes which are non-primitive. An example is shown in Figure 4 where the process "Recovery 1" was declared to be non-primitive.
Non-primitive processes can be decomposed further. For each of these processes additional viewpoints were instantiated. This is captured by the domain-independent inter-viewpoint rule (IOF1) in Table 2. The viewpoint in Figure 3 is a decomposition of the non-primitive process "Set Skip Bit" in the viewpoint shown in Figure 2.

Rule Name	Rule Definition
(IOF1)	*For each non-primitive process there exists a viewpoint instantiated from either the IOF template or the DFD template.*

Table 2: *A domain-independent rule for the IOF template.*

The DFD template facilitated a more detailed representation of (parts of)


Domain: RT Failure Detection
Template : Input-Output Flow
in
A, notB, notC
Set Skip Bit
e,c,w indicators' values,
failure status = failed for RT
out
in
A, B, notC
Switch to Backup RT
e,c,w indicators' values,
failure status = failed for RT,
not perform transaction error
detection on RT for TBD time
out

Glossary:

A = Errors of CSE_RTSA messages occur in two consecutive processing frames.
B = Backup RT is available.
C = Transaction errors are from multiple RTs.

Domain-dependent in-viewpoint rules:

(1) The processes "Set Skip Bit" and "Switch to Backup RT" are non-primitive.

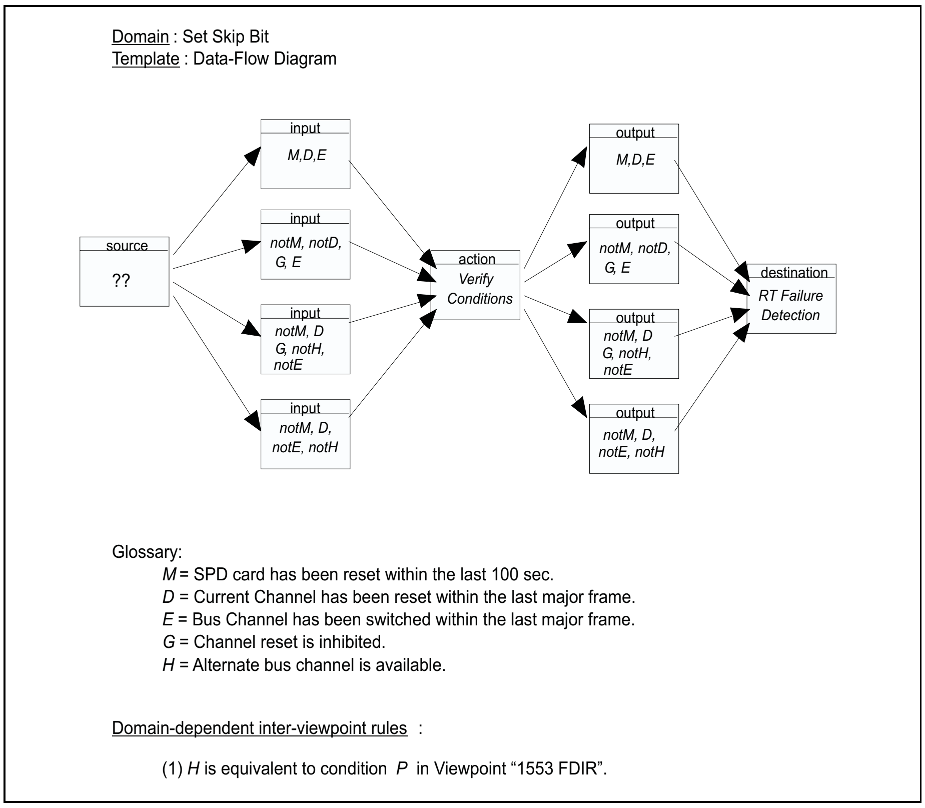
Domain-dependent inter-viewpoint rules:

(1) RT can be equal to C&C MDM in Viewpoint "MDM Recovery Management".
(2) RT can be equal to the MDMs in Viewpoint "MDM Recovery Management".
(3) The output "*failure status = failed for RT*" can be equivalento to the inputs "*Detect Failure of C&C MDM*" and "*Indication MDM has failed*" *in Viewpoint* "MDM Recovery Management".
(4) The TBD time is in relation with the time to reinitialise an RT in Viewpoint "Perform Initialisation".
(5) The input "*A*" is equivalent to the conjunction of conditions "*[a,b,c,d]*" in Viewpoint "1553 FDIR".

Figure 2: *RT Failure Detection – A lower-level IOF viewpoint.*

functions. These were given in terms of actions, inputs used by the actions and outputs produced by the action, the sources which generate the inputs and the destinations which use the outputs. Sources and destinations can themselves be other functions or processes described in the specification. An example of a DFD-based viewpoint is shown in Figure 3.

The last template used in the restructuring was the STD template. This was used to represent the general behaviour of the 1553 FDIR function described in a flowchart in the original specification. It describes a series of different boolean conditions (or events) and their associated intermediate internal states which are covered by the 1553 FDIR function in order to detect what type of failure has occurred and what kind of recovery action to take. Recovery actions are processes external to the 1553 FDIR. The STD template represented this kind of flowchart specification by associating each internal and external state with a box, each boolean value of each condition with an arrow going from one box (state) to another, and declaring by means of an domain-dependent in-viewpoint rule which of the states was an external recovery state. Part of this STD-based viewpoint is shown in Figure 5.



Glossary:

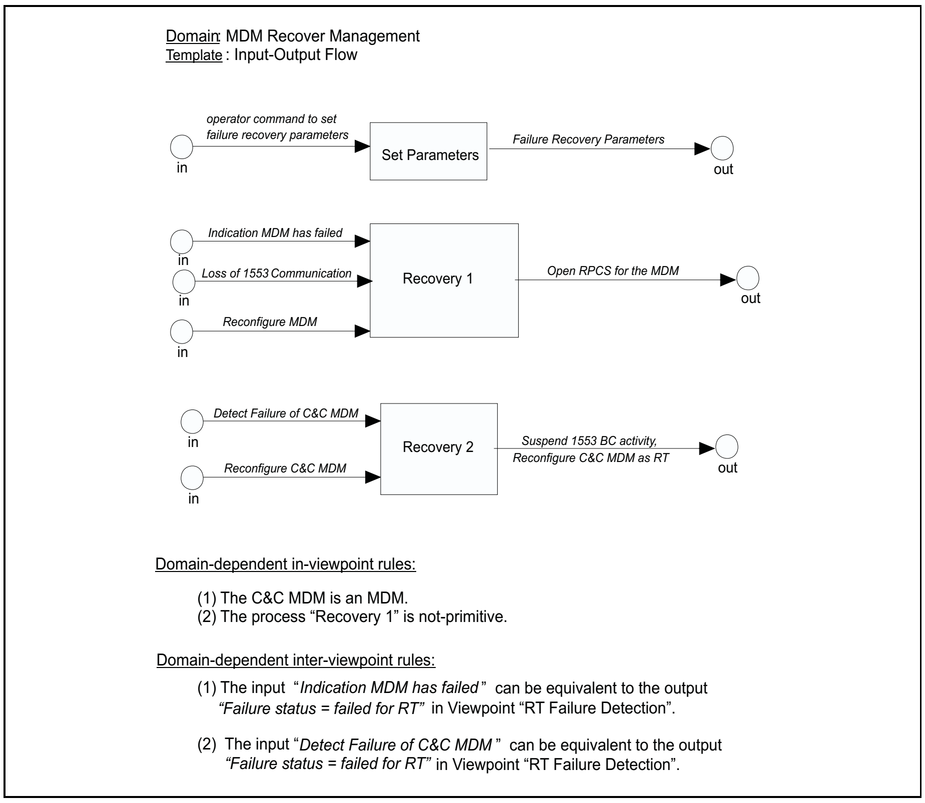
- *M* = SPD card has been reset within the last 100 sec.
- *D* = Current Channel has been reset within the last major frame.
- *E* = Bus Channel has been switched within the last major frame.
- *G* = Channel reset is inhibited.
- *H* = Alternate bus channel is available.

Domain-dependent inter-viewpoint rules :

(1) *H* is equivalent to condition *P* in Viewpoint "1553 FDIR".

Figure 3: *Set Skip Bit – A lower-level DFD viewpoint.*

Enriching the structure with inter-viewpoint rules Having defined a collection of viewpoint templates and some basic inter-viewpoint relationships between them, we then elicited further implicit relationships between viewpoints to enrich the existing structure. For the case of the IOF template, for example, the rules (IOF3) and (IOF4) shown in Table 3 were defined to capture data flows between functions. They are dictated partly by the syntactic properties of the templates – input/output arrows in the IOF and inputs/outputs in the DFD template denote the same class of object, and partly by the definition of domain-dependent inter-viewpoint rules which establish "ontological overlaps" [14] between input/output data of different viewpoints. Rule (IOF3) defines a relationship between the RT Failure Detection function, described in Figure 2, and the MDM Recovery Management function, described in Figure 4, which states that any RT failure detected by the first function is recovered by the second function. Such a link was not expressed in the original specification document, and the document structure itself would have not facilitated its identification since the constituent specifications were parts of two different


Domain: MDM Recover Management
Template : Input-Output Flow
operator command to set failure recovery parameters
in
Set Parameters
Failure Recovery Parameters
out
Indication MDM has failed
in
Loss of 1553 Communication
in
Reconfigure MDM
in
Recovery 1
Open RPCS for the MDM
out
Detect Failure of C&C MDM
in
Reconfigure C&C MDM
in
Recovery 2
Suspend 1553 BC activity, Reconfigure C&C MDM as RT
out

Domain-dependent in-viewpoint rules:

(1) The C&C MDM is an MDM.
(2) The process "Recovery 1" is not-primitive.

Domain-dependent inter-viewpoint rules:

(1) The input "*Indication MDM has failed*" can be equivalent to the output *"Failure status = failed for RT"* in Viewpoint "RT Failure Detection".

(2) The input "*Detect Failure of C&C MDM*" can be equivalent to the output *"Failure status = failed for RT"* in Viewpoint "RT Failure Detection".

Figure 4: *MDM Recovery Management – A viewpoint from the IOF template.*

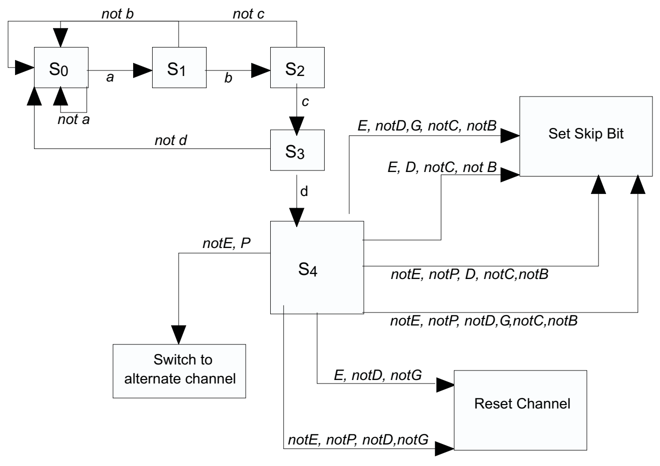
document sections. Finally, the domain-independent in-viewpoint rule (IOF2) in Table 3, was defined to express the consistency constraint that each data input and output is uniquely associated with a single process.

Similar rules were defined for the DFD template, also taking into account information about the source and destination of inputs and outputs respectively. Two example rules are shown in Table 4. Examples of viewpoints validating rule (DFD1) are the "RT Failure Detection" and the "Set Skip Bit" viewpoints (shown in Figures 2 and 3 respectively).

Finally, domain-independent inter-viewpoint rules were defined for the STD template. This facilitated the identification of various inconsistencies within the 1553 FDIR function, by explicitly stating relationships between the general 1553 FDIR behavioural model and the individual specifications of the different types of failure detections covered by this function. These are shown in Table 5. The next section describes the inconsistencies identified by these rules for the process "Set Skip Bit" in the IOF-based viewpoint RT Failure Detection.

Domain-dependent in-viewpoint and inter-viewpoint rules were also defined.

Domain: 1553 FDIR
Template : State Transition Diagram



Domain-dependent in-viewpoint rules:

(1) "Switch to alternate channel", "Reset Channel" and "Set Skip Bit" are external recovery states.

Domain-dependent inter-viewpoint rules:

(1) The set of conditions "*[a,b,c,d]* " is equivalent to the input "*A*" in Viewpoint "RT Failure Detection".
(2) The condition "*P*" is equivalent to the input "*H*" in Viewpoint "Set Skip Bit".

Figure 5: *Part of 1553 FDIR – A high-level STD viewpoint.*

These represented either some explicit glossaries about domain-specific terms which were already given in the specifications (e.g., in-viewpoint rule (1) in Figure 4), some domain-specific relationships between different terms which were elicitated by our analysis (e.g., the inter-viewpoint rules in Figures 2 and 4), or by some common sense interpretation of the English text descriptions (e.g., the inter-viewpoint rules in Figure 5). Figure 6 summarises some of the inter-viewpoint rules that enriched the structure of the original specification documents.

3.2 Identifying inconsistencies

The restructured representation of the two informal requirements documents, facilitated the detection and analysis of existing inconsistencies, expressed as violations of in-viewpoint and inter-viewpoint rules. The rules affected were among those added during the enriching phase of the approach, for which no

Rule Name	Rule Definition
(IOF2)	*Arrows have different labels*
(IOF3)	*Outputs in an IOF viewpoint are in relation with inputs in any VP A, instantiated either from the DFD or from the IOF template, whenever they have the same name or stated to be equivalent.*
(IOF4)	*Inputs in an IOF viewpoint are in relation with outputs in any VP A, instantiated either from the DFD or the IOF template, whenever they have the same name or are stated to be equivalent.*

Table 3: *Additional domain-independent rules for the IOF template.*

Rule Name	Rule Definition
(DFD1)	*The outputs of a DFD viewpoint are inputs to any viewpoint A instantiated from the IOF template, whenever the destination of these outputs is equal to the domain of the viewpoint A.*
(DFD2)	*The inputs of a DFD viewpoint are outputs from any viewpoint A instantiated from the IOF template, whenever the source of these inputs is equal to the domain of the viewpoint A.*

Table 4: *Additional domain-independent rules for the DFD template.*

explicit corresponding definition existed in the original specification. Manual inspections of these documents would therefore have made the identification of such inconsistencies more difficult.

The first inconsistency identified related to the violation of the domain-independent in-viewpoint rule (IOF2) in the MDM Recovery Management viewpoint (see Figure 4). Using the domain-dependent rule "C&C MDM is an MDM", the input "Reconfigure MDM" to the process Recovery 1, can be rewritten as "Reconfigure C&C MDM" whenever the MDM being considered is the C&C MDM. For this particular case, this input label to the process Recovery 1 becomes equal to the input label "Reconfigure C&C MDM" of the process Recovery 2, so violating the in-viewpoint rule (IOF2). Intuitively, the domain-dependent rule expresses a domain-specific overlap between the two terms MDMs and C&C MDM which implies that the function MDM Recovery Management is not able to choose which alternative process (Recovery 1 or Recovery 2) to activate whenever there is a request to reconfigure the C&C MDM.

Various other inconsistencies were identified within the 1553 FDIR function

Rule Name	Rule Definition
(STD1)	*For each external process X, if there exists a viewpoint A of type IOF which includes the process X, then for each path leading to X, there exists an identical set of inputs to X in the VP A.*
(STD2)	*For each external process X, if there exists a viewpoint A of type DFD with domain equal to the process X, then for each path leading to X, there exists an identical set of inputs in the VP A.*

Table 5: *Additional domain-independent rules for the STD template.*

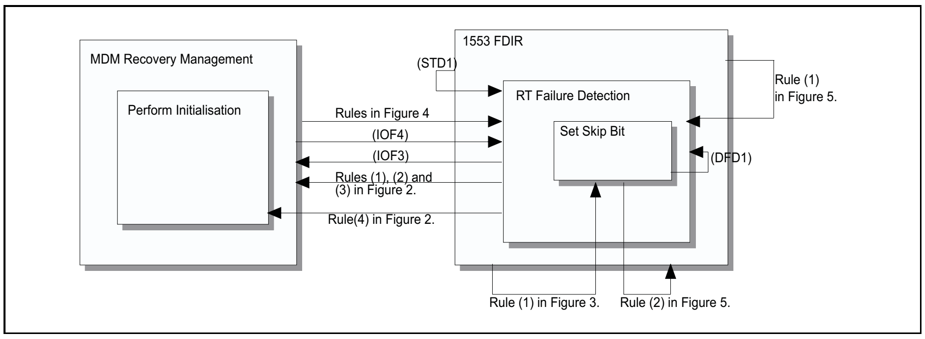


Figure 6: *The restructured requirements specifications with some inter-viewpoint rules.*

– at least one for each type of failure detection. Only one example is described here, as the others were detected in a similar way by means of the same domain-independent inter-viewpoint rule of the 1553 FDIR viewpoint. The example involves the part of 1553 FDIR viewpoint described in Figure 5 and the RT Failure Detection viewpoint described in Figure 2. In this case, it is the domain-independent rule (STD1) which was violated, where the process X is equal to "Set Skip Bit". The reasoning process which "proved" the violation of this rule is more complex than that described for the previous inconsistency and is composed of the following steps.

1. In the RT Failure Detection viewpoint, the process "Set Skip Bit" is non-primitive. This implies, by the inter-viewpoint rule (IOF1), that there exists another viewpoint with domain "Set Skip Bit" which specifies this process further.

2. The application of rule (IOF1) also involves the Set Skip Bit viewpoint (see Figure 3). The inter-viewpoint rule (DFD1) in this viewpoint implies that the alternative four sets of outputs are also alternative four sets of inputs

to the viewpoint RT Failure Detection, and therefore to each process it describes.

3. Rule (DFD1) implies that the total inputs to the process “Set Skip Bit” in the viewpoint RT Failure Detection are four alternative sets of data given by the four sets of outputs of the Set Skip Bit viewpoint extended with the inputs already given in the RT Failure Detection for this process.
4. The domain-dependent rule (5) in the RT Failure Detection viewpoint, involving data of the 1553 FDIR viewpoint, implies an equivalent rewriting of these four alternative sets of inputs.
5. All alternative paths leading to the process Set Skip Bit in the viewpoint 1553 FDIR are computed. Again, there are four.
6. Each of these paths is compared with each alternative set of inputs generated in step 4.

The last step is an attempt to validate the (STD1) domain-independent inter-viewpoint rule. In fact, it was violated, indicating an inconsistency between the 1553 FDIR and the RT Failure Detection viewpoints. In particular, there was no set of inputs which is comparable to any of the alternative paths in the 1553 FDIR viewpoint. Checking the (STD1) rule for each of the alternative paths, we found four inconsistencies as the rule is violated in each of these cases.

Finally, another inconsistency was identified between the RT Failure Detection and the MDM Recovery Management functions. This was not a direct violation of a rule but a consequence of the application of an inter-viewpoint rule. In the RT Failure Detection viewpoint, if inputs A, $notB$ and $notC$ occur, the failure status of the RT under consideration is set to “failed” and the failure detection process (of the C&C MDM CSCI system) continues, since no backup RT is available (i.e. $notB$) to recover from the failure. Using the domain-dependent rule, the RT can be the C&C MDM. The inconsistency arises when the RT is in fact the C&C MDM. By the inter-viewpoint (IOF3) and the domain-dependent rule (3) in RT Failure Detection (Figure 2), the output “failure status = failed for RT” is equivalent to the input “Detect Failure of C&C MDM” in MDM Recovery Management. In the MDM Recovery Management viewpoint, it is stated that the process Recovery 2 under this input, stops the failure detection process, to reconfigure the C&C MDM as a general RT. These two specifications are therefore not consistent. Two contradictory statements (“continue failure detection process” in the RT Failure Detection viewpoint and “stop failure detection process” in the MDM Recovery Management viewpoint) are specified.

3.3 Analysing evolutionary changes

As we indicated in Section 2, inter-viewpoint rules in our viewpoint-based restructuring approach are the only basis for detecting inconsistency and managing change propagation. In the previous section we discussed the application of the approach for detecting inconsistencies in two informal requirements specifications. We now discuss how we used the approach to manage evolutionary changes in the same informal specification documents. Our original specification document was the "June" version - we also examined two earlier versions (February and April) and one later version (August). For brevity, we only summarise our results below.

The first step was to examine if the requirements document structure was loosely preserved in each of these versions. The major changes we found were (i) the existence of an additional section on "MDM Recovery Management" in the April version, (ii) some paragraphs of the subsection "Bus Channel" in April's version becoming themselves subsections of the same level as the Bus Channel in June's version, and (iii) again in June's version, the fusion of different subsections specifying the MDM Initialisation function for each type of MDM, into only one general subsection referring to a table summarising the different type of MDMs. For these major changes, the hierarchic structure of viewpoints and the basic inter-viewpoint rules was, in general, preserved. In case (i) the addition of more specifications facilitated the identification of more inter-viewpoint rules for the IOF template. For instance, rule (IOF3), which facilitates cross-section relationships between the MDM Recovery Management and 1553 FDIR functions, was meaningless in February's version, as the MDM Recovery Management function was missing in that version. Such a rule became useful from April's version onwards, when the function MDM Recovery Management was added to the specifications. In case (ii), the hierarchic tree structure defined for April's version was changed by moving some viewpoints from being subnodes of the node "Bus Channel" to becoming, together with the Bus Channel, subnodes of the 1553 FDIR node. Of course wherever necessary, some of these viewpoints were reformulated with the correct template in order to preserve the inter-viewpoint rules (HT1) and (HT2). In case (iii), the hierarchic tree structure defined for April's version was further changed by joining together the viewpoints describing the MDM Initialisation function for each type of MDM into one viewpoint only. This determined the addition of a domain-dependent in-viewpoint rule which defined the domain of the possible MDMs.

Various other minor changes were made in these four versions of the specification. These were mainly changes within the specifications of some functions. Interesting ones included the changes made to the the 1553 FDIR flowchart and its associated text descriptions. In each version, the flowchart was gradually extended by introducing either more intermediate conditions or more external failure detections. Text descriptions of these failure detections were consequently updated or added. For each of these changes, using the inter-viewpoint rules, we were able

1. to identify the related parts of the specifications which had been affected by the changes,

2. to define the types of changes that needed to be made in order to preserve consistency, and

3. to map back into the specifications to check whether these changes were actually made to the specification.

Our investigation showed that, in most cases, additional inconsistencies were introduced by the evolutionary changes. The changes were not consistently traced within the specifications – variations were made in some parts of the document only, leaving other related specification fragments unchanged. We believe that many of these inconsistencies arose because the relationships between many specification fragments were left implicit. We believe that our restructuring approach helped overcome this problem by providing a way for explicitly representing many of these relationships as inter-viewpoint rules.

4 Lessons Learned

We have described our experience in applying our restructuring approach to an existing informal requirements specification. We now discuss the lessons we learned from this experience, indicating how the approach facilitated our analysis, inconsistency handling and change management.

4.1 Decomposition.

In our case study, we decomposed the informal specification documents in two steps. First, different high-level viewpoints were defined for each section and subsection of the documents. These tended to be more stable than other lower-level viewpoints. Their viewpoint rules were often definitions of hierarchic (parent-child) relationships. The second step *refined* the first decomposition. Additional viewpoints were defined that encapsulated the different parts of the same (sub)section in more detail. The result was a "subsystems" hierarchical decomposition of the specifications dictated partly by the document structure and partly by a careful cross-section analysis of the specifications. At this stage, viewpoints were treated as "black boxes" – simply associated with the different parts of the specifications.

In general, different criteria could be adopted for decomposing the problem (requirements specification) into parts (viewpoints). For example, viewpoints could be defined for each individual component (or function) of the system described in the original specification, for each representation scheme used in the specification, or for each section and subsection of the specification (that is, decomposing using the existing *document structure*). Since we were not experts in the domain of the case study, the first option was clearly not easy to adopt. Moreover, the second option of decomposing on the basis of the representation styles used in the specification would have lead to an insufficiently fine granularity for the structure to be useful[3]. On the other hand, our experience suggests that the document structure of such specifications reflects a first level

[3]It is often the case, as in our case study, that informal specifications are written, almost entirely, in natural language.

of decomposition into major subsystems, and it was also generally preserved as the specifications evolved.

Lesson 1 Decomposition based on an existing document structure does not require any expertise in the domain of the specification, and provides a path back to the original specification after analysis and processing is performed on the new structure. Moreover, the resulting structure is generally stable as the original specification documents evolve.

4.2 Representation.

While translating (parts of) a specification does not, strictly speaking, fall within the realms of restructuring, there are advantages that may be accrued from such a translation process (some even argue that the most significant benefits gained from using formal methods are the result of the formalisation process itself! [11]). The second stage of our approach therefore allows the representation of the different viewpoint specifications in different notations which may include the original notation in which they were expressed. The choice of representation scheme for different viewpoints also involves the expression of some basic (domain-independent) rules to define the conditions for well-formedness and internal viewpoint consistency. Examples of such rules were described in Tables 1 and 2. Of course, new domain-independent rules were also added as the restructuring process proceeded and as a better understanding of the specifications was gained.

Lesson 2 A mixture of formal and informal representation schemes may be used to represent requirements as long as the relationships between them are explicitly defined.

4.3 Enriching the viewpoint structure

As described in Section 3, the structure of a viewpoint-oriented specification is more than just a collection of different viewpoints. It is also the collection of inter-viewpoint rules that express the relationships between these viewpoints. Our approach distinguished between domain-independent and domain-dependent rules. Domain-independent rules expressed the relationships between viewpoint templates, such as the relationship between a parent "input-output flow" diagram and the child diagram that decomposes one of the parent's constituent processes. Many of these rules were defined when choosing or developing a viewpoint template representation scheme, but others were also elicited after some analysis of the actual specifications. For example, the inter-viewpoint rules listed in Tables 3, 4 and 5 were all added to the templates after a better understanding of the documents was gained through restructuring.

Domain-dependent rules, expressed the relationships between actual specification fragments, such as “ontological overlaps” [14] denoting synonyms in the problem domain. These were of different types. For instance, the domain-dependent rule (1) in Figure 4 expressed an in-viewpoint ontological overlap between the terms MDMs and C&C MDM, whereas the domain-dependent rule (3) in Figure 2 expressed an “intersection” between the two different functions RT Failure Detection and MDM Recovery Management. This itself was based on the ontological overlap expressed by the domain-dependent inter-viewpoint rules (1) and (2) in Figure 2. Finally, the domain-independent rule (STD1) expressed an “inclusive” overlap between the general 1553 FDIR function and the function RT Failure Detection.

Lesson 3 Inter-viewpoint rules are the basis upon which consistency is checked and change propagation is managed. They are also the measure of ‘completeness’ in this context.

4.4 Analysis.

Our case study suggested that many inconsistencies in a large monolithic informal specification include much information that is implicit. For example, the first inconsistency described in Section 3.2 was related to the implicit assumption that each process described in the MDM Recovery Management specification is assigned to different failure conditions. Similarly, the inconsistency between 1553 FDIR and RT Failure Detection viewpoints was related to the implicit common sense assumption that being the general failure detection behaviour of the 1553 FDIR specification ought to be reflected in the text description of each individual type of failure detection. The third type of inconsistency described in Section 3.2 was based on implicit assumptions about the existence of an interface between the RT Failure Detection and the MDM Recovery Management functions. The restructuring approach facilitated the identification of such implicit assumptions, defining them explicitly as rules. Inconsistencies were then identified by either checking these rules, or by using them to integrate parts of the specification in order to prove their consistency.

What added confidence to our analysis was that some of the inconsistencies identified by our study were also identified by NASA’s Independent Validation & Verification (IV&V) group, who used a different approach based on modelling informal specifications using formal methods such as SCR and PVS [10]. While the results of NASA’s and our approaches are comparable – similar inconsistencies were identified in the 1553 FDIR function – we believe that our approach provided a much “cheaper” alternative to wholesale formalisation of the original specification documents.

Nevertheless, given a structure of related viewpoints that represents a requirements specification, different analysis techniques may be deployed to validate the requirements and to check their consistency. In previous work for example [6], we used an adaptation of classical logic to perform some kinds of analysis, while in other work [2] informal inspection was sufficient. The approach we have used in the case study combined informal inspections with some automated support using Prolog (discussed later).

Lesson 4	The viewpoints structure made the specifications more amenable to analysis (both manual and automated).

4.5 Inconsistency handling and change management

The expectation is that analysis will necessitate taking action to handle inconsistencies [4]. Acting in the presence of inconsistency is still an open research issue, so we adopted a simple approach of consulting the domain experts when faced with such inconsistencies.

Nevertheless, we found that the identification and explicit formalisation of relationships within and between parts of the specification facilitate change management. The analysis of different versions of the same documents illustrated that additional inconsistencies were often caused whenever a change was made to the specifications. The lack of explicit relationships within the original specifications meant that any addition of new specification information was often not propagated to related parts of that specification. For example, in each version of the original specifications, extensions of the flowchart of the 1553 FDIR function were not propagated in the related failure detection text descriptions, and vice-versa. Moreover, changes made in order to resolve existing inconsistencies also caused additional inconsistencies [3]. An example was in June's version of the 1553 FDIR function, where the flowchart was changed to solve some inconsistencies with the text descriptions present in the April version, but the related text description was not changed consistently, thus causing the additional inconsistencies described in Section 3.2. The explicit relationships between the 1553 FDIR viewpoint and the viewpoints of the text descriptions (e.g., RT Failure Detection) would have helped avoid such additional inconsistencies, so guaranteeing a consistent evolution of the documents.

Lesson 5	In-viewpoint and inter-viewpoint rules (whether domain-independent or domain-dependent) provide explicit information which is often missing in specifications and which is needed for consistent change management. Indeed, the impact of evolutionary changes can be traced, using these rules to check consistent change propagation to related parts.

As with the analysis, the advantage of this approach is that it is not expensive in either time or effort. In our case study, the document structure was generally preserved. Thus, evolutionary changes like addition, fusion or elimination of chunks of specification did not imply a major reorganisation of the document structure. Consequently, once a restructured representation of a version was developed, the modelling of subsequent versions was built upon this representation. Other methods, such as the formal modelling approaches used in [10], are much more costly in that the modelling of new versions requires a re-modelling of the specifications.

We also learned from our experience of automating parts of our approach. The natural language representation style of the informal specifications did not allow a fully automated process for restructuring and representing these documents into viewpoints. A manual process was needed to provide the viewpoints structure and the related rules. However, the resulting viewpoint structure was far more amenable to translation into formal languages (such as Prolog) to provide automated support for consistency checking. This was easier to achieve than translating the original natural language specification into a formal language. Moreover, given that changes to the specifications were, in most cases, not drastic, the restructured representation was preserved during the evolution of the documents.

Lesson 6 The manual effort of representing the specifications as viewpoints need be invested only once and then the specifications may be analysed semi-automatically in the subsequent versions.

5 Related Work

A number of related approaches have used partial formal modelling to analyse and validate existing informal requirements specifications. For example, the work of Easterbrook *et al.* [10] describes the use of formal methods such as SCR [16] and PVS [15] to model the same informal requirements examined in this paper. This work describes selective modelling of the most critical parts of a requirements specification, and the testing of some critical properties. As in our work, the approach does not aim to guarantee completeness and correctness of the existing specifications, but to increase confidence in such specifications by identifying inconsistencies and feeding the results back into the requirements development process. The inconsistencies identified and discussed in [10] include some of the same inconsistencies identified by our own restructuring approach, as well as some additional inconsistencies relating to the dynamic properties of the underlying system.

Our restructuring approach, however, could be used in conjunction with other formal modelling approaches (such as SCR), by mapping particular viewpoints into the chosen formal model (such as an SCR model). The Safety Checklists proposed by Lutz [12], for example, could also complement our approach. Checklists of properties about interface requirements in safety-critical systems could be used to enrich our restructuring process by modelling them as in-viewpoint and inter-viewpoint domain-dependent rules.

Of course, restructuring specifications has been a topic of considerable interest and research in the past. Most notably, Statecharts [17] attempt to reduce the complexity of specifications modelled as state-transition diagrams by using clustering of states into superstates. Statecharts have been used successfully by Heimdahl, Leveson and others [19, 13] to restructure formal, state-based specifications. While such approaches provide powerful (and automated) tools to analyse formal specifications, they are not suitable for analysing informal specifications that may deploy multiple representation schemes, such as the ones we have described in this paper.

Finally, recent work on formal requirements analysis [20] recognises the need to devise practical ways of structuring the V&V process in order to make it methodologically suitable for large scale analysis. The work described in this paper is a first step in this direction.

6 Conclusions and Future Work

This paper has described our experiences in *restructuring* multi-perspective requirements specifications in order to identify and analyse inconsistencies and manage change. Our restructuring approach comprises of three main activities: (1) decomposing the specifications into parts, (2) representing these parts within viewpoints using of different representation styles, and (3) enriching the resulting structure of viewpoints by identifying and explicitly defining in-viewpoint and inter-viewpoint rules that express specific relationships between different templates, and domain-specific properties within and between the different specification fragments. Using these we were able to check consistency and completeness, and track and analyse evolutionary changes in the original requirements specification.

While a large proportion of the approach can be (and was) performed manually, it is nevertheless amenable to automated support. We have developed a toolkit to support viewpoint development and inconsistency analysis. The tool provides a web-based front-end (written in Java) which facilitates the specification of viewpoints by using a set of predefined templates. For each of these templates, a class of domain-independent in-viewpoint and inter-viewpoint rules were predefined and subsequently checked by a Prolog engine. Different graphical viewpoint instantiations are converted at run-time into Prolog and checked for consistency. Changes to viewpoints are made using the web-based tool and also checked for consistency using the Prolog reasoning engine. An example of a Prolog clause which checks the the validity of the inter-viewpoint (STD1) between viewpoints 1553 FDIR and RT Failure Detection is shown below.

```
rule1(Process,FDIR):-
        process(Process,FDIR),
        typevp(IOF,VP),
        process (Process,VP),
        nonprimitive(Process,VP),
        orinputs(Inputs,Process,VP),
        equivalentorInputs(NewInputs,Inputs,Process,VP),
        flows(Paths,s0,Process,FDIR),
        comparePathsInputs(Paths,NewInputs,Results).
```

The first three clauses after the ":-" ("if") symbol check the basic conditions for the application of the (STD1) rule – i.e. that Process is an external recovery process in the FDIR function for which there exists a viewpoint VP of type IOF which includes that Process. The other clauses correspond to the reasoning process steps described in Section 3.2, in the specific case of Process being equal to "Set Skip Bit" [4].

At the moment, the toolkit is limited in that (i) the Prolog engine presents the results of its consistency checking in Prolog format, and (ii) the domain-dependent rules are hard-coded into the system. We are currently extending this to allow users to get the results of consistency checking via the same web-based front-end and to define domain-dependent rules themselves. Thus, the user should be able to specify the related domain-dependent in-viewpoint and inter-viewpoint rules during the instantiation process of viewpoints, check consistency and get information about existing inconsistencies in the same web-based view.

We believe that the framework we have presented in this paper provides us with the infrastructure for organising specifications, detecting and analysing inconsistencies and managing change. Clearly, further work still needs to be done to determine how to act in the presence of inconsistencies. However, we believe that incremental contributions towards this long term goal can be achieved by complementing our approach with existing work on inconsistency handling that combines both formal (e.g., logic-based) [6] and human-centered [2, 18] approaches.

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[4]Note that the clause "*orinputs(Inputs,Process,VP)*" checks steps 2 and 3 together.

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