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Building traceable Event-B models from requirements

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ABSTRACT

Bridging the gap between informal requirements and formal specifications is a key challenge in systems engineering. Constructing appropriate abstractions in formal models requires skill and managing the complexity of the relationships between requirements and formal models can be difficult. In this paper we present an approach that aims to address the twin challenges of finding appropriate abstractions and managing traceability between requirements and models. Our approach is based on the use of semi-formal structures to bridge the gap between requirements and Event-B models and retain traceability to requirements in Event-B models. In the stepwise refinement approach, design details are gradually introduced into formal models. Stepwise refinement allows each requirement to be introduced at the most appropriate stage in the development. Our approach makes use of the UML-B and Event Refinement Structures (ERS) approaches. UML-B provides UML graphical notation that enables the development of data structures for Event-B models, while the ERS approach provides a graphical notation to illustrate event refinement structures and assists in the organisation of refinement levels. The ERS approach also combines several constructor patterns to manage control flows in Event-B. The intent of this paper is to harness the benefits of the UML-B and ERS approaches to facilitate constructing Event-B models from requirements and provide traceability between requirements and Event-B models.

1. Introduction

We present an approach for incrementally constructing a formal model from informal requirements with the aim of retaining traceability to requirements in models. The approach helps to identify appropriate modelling elements from requirements, assists the construction of a formal model, and facilitates layering the requirements and mapping the informal requirements to traceable formal models. Traceability supports the process of validation of the model against the requirement document and allows missing requirements to be identified and captured by the model.

Our approach is based on the Event-B formal method [1]. Event-B is a refinement-based formal method with tool support for developing various kinds of systems. We make use of UML-B [2] and Event Refinement Structure (ERS) [3,4]. UML-B provides graphical modelling based on UML which supports the development of an Event-B formal model. The visual view of the system provided by UML-B and ERS assists in the development of the refinement strategy before the actual work on modelling is performed. The combined ERS diagrams, which show the overall refinement structure of the system, can be modified until an acceptable refinement structure is reached. In addition, the ERS approach provides several constructor

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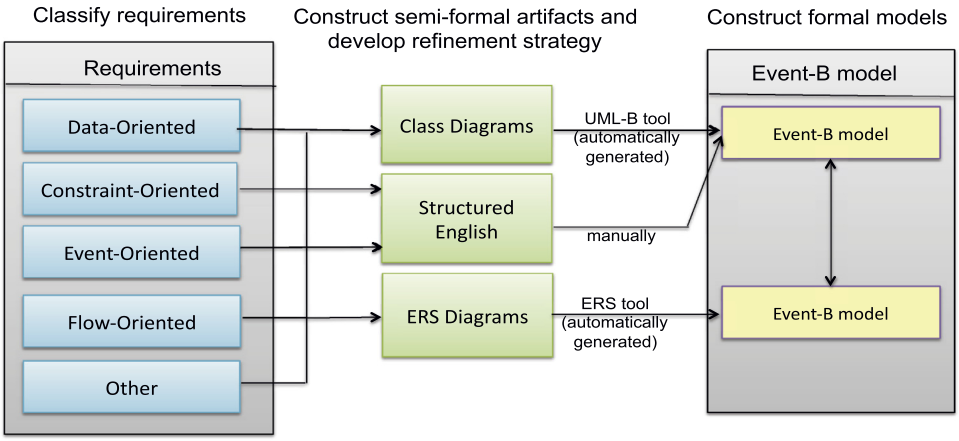


Fig. 1. Steps for constructing traceable formal models.

patterns that can be used to manage the flow of events and define event ordering. Moreover, Event-B models corresponding to ERS diagrams and UML-B diagrams can be generated automatically by the ERS plug-in [5] and the UML-B plug-in [6].

Our approach comprises of three stages, which are shown in Fig. 1.

The first step in our approach is requirement classification. Requirements are classified based on Event-B modelling structures. The classification consists of five classes: data-oriented, constraint-oriented, event-oriented, flow-oriented, and others. Data-oriented requirements represent attributes and relationships between attributes, constraint-oriented requirements represent conditions that must remain true in the system, event-oriented requirements represent the activities of the system and its components, flow-oriented requirements represent relationships between events, and "others" represent other requirements that do not fit into the previous classes.

The second step consists of three stages. Firstly, we use semi-formal artifacts described using UML-B, ERS diagrams and structured English to represent requirements. UML-B is used to represent data-oriented requirements. ERS is used to represent flow-oriented requirements. The structured English is a way of breaking down constraint and event-oriented requirements into shorter sub-requirements and mapping each sub-requirement to the appropriate requirement class (constraint or event-oriented). The semi-formal artifacts serve as an intermediate representation between requirements and the Event-B formalism. Representing requirements using semi-formal artifacts is reasonably simple, and at the same time the movement from the semi-formal artifacts to Event-B is straightforward. Secondly, we merge the fragmented structured English of a single event together to facilitate tracing the event components. Thirdly, we combine ERS diagrams and use these diagrams to assist the process of developing the refinement strategy.

The third step is to use the UML-B tool and the ERS tool to generate Event-B models and also manually write the corresponding Event-B from the structured English representation.

The work presented in this paper is an extension of [7]. In this paper we apply our approach to a new case study (queue management in an operating system) and add more information regarding the verification of constructed Event-B models using Rodin. In addition we discuss the use of the shared-event composition technique to combine Event-B models generated from UML-B diagrams and Event-B models generated from ERS diagrams. Moreover, some relevant formal developments of operating systems by other researchers are discussed.

This paper is structured as follows: Section 2 gives an overview of Event-B, UML-B, ERS and shared event composition in Event-B. The description of the presented approach is introduced in Section 3. The application of the proposed approach to a queue management case study is introduced in Section 4. Section 5 introduces some related work in requirements traceability. Conclusions and future work are drawn in Section 6.

2. Preliminaries

2.1. Event-B

Event-B is a formal method developed by Jean-Raymond Abrial, which uses set theory and predicate logic to provide a formal notation for the creation of models of discrete systems and the undertaking of refinement steps. Event-B is supported by the Rodin toolset [8,9], which includes various plugins for features such as theorem-proving, model-checking, model composition and decomposition and translation of diagrammatic representations to textual representation. An abstract Event-B specification can be refined by adding more detail and bringing it closer to an implementation. A refined model in Event-B is verified through a set of proof obligations expressing that it is a correct refinement of its abstraction. Event-B may be used for parallel, reactive or distributed system development. Event-B models contain two constructs: a context and a machine. The context is the static part of a model in which fixed properties of the model (sets, constants, axioms)

```
machine M1 refines M0  sees C0

variables Event1 Event2
invariants
  @inv1 Event1 ⊆ PAR_SET
  @inv2 Event2 ⊆ Event1
  @inv3 Event2 = AbstractEvent

event INITIALISATION then
     @act1 Event1 ≔ ∅
     @act2 Event2 ≔ ∅
end

event Event1 any par  where
     @grd1 par ∉ Event1
    then
     @act1 Event1 ≔ Event1 ∪ {par}
end

event Event2 refines AbstractEvent
   any par where
     @grd1 par ∈ Event1
     @grd2 par ∉ Event2
   then
     @act1 Event2 ≔ Event2 ∪ {par}
end
```

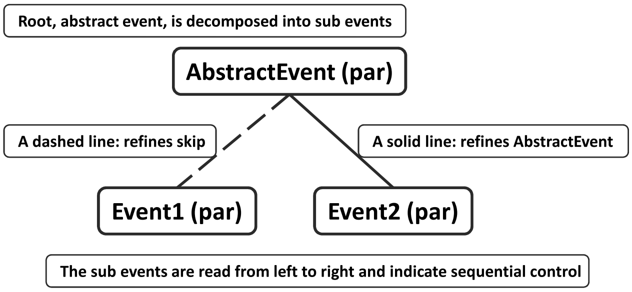


Fig. 2. Event Refinement Structure diagram.

are defined. The dynamic functional behaviour of a model is represented in the machine part, which includes variables to describe the states of the system, invariants to constrain variables, and events to specify ways in which the variables can change.

2.2. UML-B

UML-B is a diagrammatic notation based on UML and Event-B. It provides a graphical modelling environment that allows the development of an Event-B formal model through the use of UML graphical notation. There are four types of UML-B diagrams, namely package diagrams, context diagrams, class diagrams and state machine diagrams. Package diagrams represent the structure and the relationships between Event-B contexts and machines. A context diagrams describes the context part of an Event-B model. Class diagram and state machine diagrams describe state and behaviour. Class diagrams in UML-B may contain attributes (variables), associations (relationships between two classes), events and state machines (transitions between states). State machine diagrams describe the behaviour of instances of classes as transitions linked to events.

UML-B supports the notion of refinement. It is possible to introduce a class in a refined machine that refines a class of its abstract machine. A refined class can keep all attributes of its abstract class, corresponding to the case where a refined machine keeps all the variables of an abstract machine. It is also possible that a refined class drops some of the attributes of the abstract class, corresponding to the case of removing variables through performing data refinement. Moreover, a refined class can introduce new attributes in the class diagram, corresponding to the case of introducing new variables in the refinement levels.

2.3. Event refinement structure approach

Although refinement in Event-B provides a flexible approach to modelling, it has the weakness that it cannot explicitly represent the relationships between abstract events and new events introduced in a refinement level. The ERS approach addresses this limitation. The idea is to augment Event-B refinement with a graphical notation that is capable of representing the relationships between abstract and concrete events explicitly. Using the ERS approach has another advantage, namely that it allows event ordering to be represented explicitly. Fig. 2 illustrates these two features of the ERS graphical notation.

Assume machine *M1* on the left hand side of Fig. 2 refines some machine *M0* which contains the abstract specification of *AbstractEvent*. The machine *M1* encodes its control flow (ordering between *Event1* and *Event2*) via guards on the events. This control flow is made explicit in the ERS diagram presented on the right hand side. This diagram explicitly illustrates that the effect achieved by *AbstractEvent* at the abstract level, machine *M0*, is realised at the refined level, machine *M1*, by the occurrence of *Event1* followed by that of *Event2*. The ordering of the leaf events is always from left to right (this is based on JSD diagrams [10]). The solid line indicates that *Event2* refines *AbstractEvent* while the dashed line indicates that *Event1* is a new event which refines *skip*. In the Event-B model of machine *M1* on the left hand side, *Event1* does not have any explicit connection with *AbstractEvent*, but the diagram indicates that we break the atomicity of *AbstractEvent* into two sub-events in the refinement. The parameter *par* in the diagram indicates that we are modelling multiple instances of *AbstractEvent* and its sub-events. Events associated with different values of *par* may be interleaved, thus modelling interleaved execution

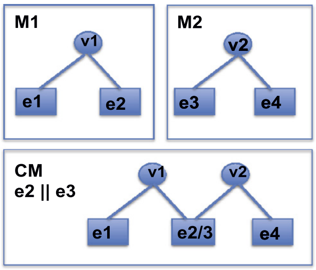


Fig. 3. Shared event composition.

of multiple processes. The effect of an event with parameter *par* is to add the value of *par* to a set control variable with the same name as the event, i.e., $par \in Event1$ means that *Event1* has occurred with value *par*. The use of a set means that the same event can occur multiple times with different values for *par*.

2.4. Shared event composition

Composition [11] is the process of composing several sub-models in a variety of styles. Shared event composition [11] enables sub-models to interact through event synchronisation. Several events can be composed in a single event. The composed event includes the conjunction of guards of sub-model events and combines the actions of sub-model events. The approach has a restriction that prevents the sub-models to include any shared variables. A tool has been developed to support this style of composition in Rodin [11].

Fig. 3 illustrates this style; suppose we have a model *M1* that has events *e1*, *e2* with variable *v1*. Model *M2* has events *e3* and *e4* with variable *v2*. *e2* updates *v1* and *e3* updates *v2* and *v1* and *v2* are independent variables. Event *e2* in *M1* and event *e3* in *M2* have the following form:

$$\begin{array}{l} e2 \triangleq \textbf{any}\ \ p \\ \quad \textbf{where} \\ \quad\quad G1(v1, p) \\ \quad \textbf{then} \\ \quad\quad v1 := E1(v1, p) \\ \quad \textbf{end} \end{array} \qquad \begin{array}{l} e3 \triangleq \textbf{any}\ \ p \\ \quad \textbf{where} \\ \quad\quad G2(v2, p) \\ \quad \textbf{then} \\ \quad\quad v2 := E2(v2, p) \\ \quad \textbf{end} \end{array}$$

We can compose *M1* and *M2* such that events *e2* of *M1* and *e3* of *M* are synchronised. The resulting composed model will share the two independent variables: *v1* and *v2* and event *e2* from model *M1* and *e3* from model *M2* are composed by conjoining their guards and combining their actions.

The resulting composed event has the following form:

$$\begin{array}{l} e2 \parallel e3 \triangleq \textbf{any}\ \ p \\ \quad \textbf{where} \\ \quad\quad G1(v1, p) \\ \quad\quad G2(v2, p) \\ \quad \textbf{then} \\ \quad\quad v1 := E1(v1, p) \\ \quad\quad v2 := E2(v2, p) \\ \quad \textbf{end} \end{array}$$

3. Steps for constructing traceable Event-B models

In use cases, the system's functionality is described through structured stories in easy-to-understand text form, from which requirements can be derived. Our objectives are to provide a link between requirements and formal models and to facilitate building traceable Event-B formal models from requirements. The following subsections describe the steps proposed to achieve these goals.

3.1. Step 1: Classify requirements

We classify requirements into the following five classes, based on the structure of Event-B models: *data-oriented* requirements, *constraint-oriented* requirements, *event-oriented* requirements, *flow* requirements, and *other* requirements. Each requirement can be placed in at least one category. A detailed description of the requirement classification, with examples of lift controller requirements taken from [12], is given below.

Table 1
Description of flow requirements.

Flow requirements	Example	Description
Sequencing requirements	*LIFT7* The floor door closes before the lift is allowed to move	The relationship between the door closing operation and the lift moving operation can be seen as a sequence. After the lift-door closes, the lift is allowed to move.
Selection requirements	*LIFT8* If a lift is stopped then the floor door for that lift may be open	In this requirement the lift door can be either opened or left closed when the lift is stopped.
Repetition requirements	*LIFT9* There might be more than one external floor request in a particular floor, the lift will respond to them (stop) only once	Here, "more" indicates the iteration of the floor request operation.

Data-oriented requirements: These are requirements that describe attributes of nouns and the relationships between nouns. Here are three examples of this requirement class:

LIFT1	Each **floor** has one **button** for requesting travelling to another floor
LIFT2	The **lift-door** can be **closed** or **opened**
LIFT3	The **lift** can be **moving** or **stopped**

The nouns "floor" and "button" in the requirement *LIFT1* are identified as data-oriented requirement. The noun "lift-door" and the attributes "closed" and "opened" in the requirement *LIFT2* are also identified as data-oriented requirement since they describe states of the door. Similarly, the noun "lift" and the attributes "moving" and "stopped" in the requirement *LIFT3* are identified as data-oriented requirement since they describe states of the lift.

Constraint-oriented requirements: These are requirements that describe properties about the data that should always remain true. They are normally identified by keywords such as *never*, *must not*, *always* etc. The following are constraint-oriented requirements:

LIFT4	The lift door of a moving lift must be closed
LIFT5	The building has 3 floors

LIFT4 describes a system property relating the position of the lift door and the lift motion whereas *LIFT5* describes a property about the maximum floor number.

Event-oriented requirements: These are requirements that describe a function or activity of the system or its components. Events are normally identified by verbs, such as the following requirement:

LIFT6	People on a floor press a button to request a lift

The verbs "press" and "request" denote that *LIFT6* is of event-oriented type. The part of an event-oriented requirement that describes conditions under which an event can happen is called a *guard* requirement, whereas the part of an event-oriented requirement that describes how the data defining the state is going to change is called an *action* requirement.

Flow requirements: These are requirements that describe the flow of events. We can classify flow requirements generally into three types: *sequence* requirements which describe sequencing between operations, *selection* requirements which describe "if–then–else" structure to indicate the selection between two or more operations, and *repetition* requirements which describe the iteration of a particular operation multiple times. Table 1 provides examples of flow requirements.

Flow requirements are not restricted to this classification. Other classes can be identified by analysing more case studies. Moreover, it is sometimes useful to group two or more requirements together that show a particular flow. This is because flow requirements can sometimes be extracted from more than one requirement, and to clarify this, we need to group requirements that show a particular flow together, and separate them from other requirement classes. This point is illustrated in Section 4.

Other requirements: Other requirements that do not fit into the previous classes can be considered in this class. This includes requirements that are more difficult to model in Event-B, such as requirements that represent fairness properties or timing properties.

3.2. Step 2: Construct semi-formal artifacts and develop refinement strategy

This step comprises of three stages, described in what follows.

3.2.1. Stage 1: Use semi-formal artifacts (UML-B, ERS, and structured English)

In the first stage, requirements are represented in a semi-formal notation depending on their type:

Table 2
Description of the ERS patterns.

Pattern	Description
sequence-/and-constructor	execute events in a sequence. The difference between sequence- and and-constructor is that and-constructor executes all available events in any order, while the sequence constructor executes events in a particular order
or-constructor	execute one or more events from two or more available events, in any order
xor-constructor	execute exactly one event from two or more
loop pattern	execute an event zero or more times
all-replicator	execute an event for all instances of a defined set
some-replicator	execute an event for one or more (some) instances of a defined set
one-replicator	execute an event for exactly one instance of a defined set

Fig. 4. The class diagram for *LIFT1*.

- **Data-oriented requirements** are represented using UML-B diagrams: nouns or attributes are represented using class diagrams, relationships between nouns are represented using UML-B associations, and transitions between different attribute values are represented using state machine diagrams.
- **Constraint and Event-oriented** requirements are represented using structured English. The structured English is a way of breaking down constraint and event requirements into smaller requirements and mapping each sub-requirement to the corresponding requirement identifier to facilitate requirement traceability.
  The structured English representation for constraint-oriented requirements has the form:

  constraint: < constraint requirement > ⟶ < *REQ* >

  The structured English representation for event-oriented requirements has the form:

  event name
  guard: < guard requirement > ⟶ < *REQ* >
  action: < action requirement > ⟶ < *REQ* >

  In the above notation, the arrow is used for tracing back to the original requirement, and *REQ* denotes the requirement identifier of the original requirement.
- **Flow requirements** are mapped to the appropriate ERS diagram according to Table 2 which summarises the behaviour of the ERS patterns. ERS has constructs that set that support several kinds of flows, therefore sequence requirements are mapped to *sequence/and* diagrams, selection requirements are mapped to *or/xor* diagrams, and repetition requirements are mapped to *loop/all/some replicator* diagrams.

Representing requirements with graphical/structured English notation provides an intermediate level between requirements and models and enables the validation of the model against the requirements. Assuming that requirements are analysed based on the described requirement classification, the following examples illustrate how to represent each requirement class in a graphical or structured English notation.

The data-oriented requirement ***LIFT1*** which is introduced in step 1 is represented with a class diagram as shown in Fig. 4.

The class *Floor* consists of the attribute *FloorButton* of type boolean that indicates whether there is a request for the lift to stop at that floor. The multiplicities correspond to the mathematical categorisations of functions: partial, total, ..etc. The multiplicity of the attribute *FloorButton* and instance set for *Floor* is (0..n). (0..n) means that there is a boolean value for each floor.

The data-oriented requirement ***LIFT2*** is represented using the state machine in Fig. 5, which shows two states, “open” and “close”, and two transitions *OpenLiftDoor* and *CloseLiftDoor*.

The data-oriented requirement ***LIFT3*** is represented using the state machine in Fig. 6, which shows two states, “stopped” and “moving”, and two transitions *LiftStop* and *LiftMoving*.

The constraint-oriented requirement ***LIFT4*** is represented as an English constraint as shown in Fig. 7.

The constraint-oriented requirement ***LIFT5*** is represented as an English constraint as shown in Fig. 8.

The event-oriented requirement ***LIFT6*** is represented as structured English as shown in Fig. 9.

Fig. 5. The state machine diagram for *LIFT2*.

Fig. 6. The state machine diagram for *LIFT3*.

constraint: The lift door of a moving lift must be closed ⟶ *LIFT4*

Fig. 7. The structured English of *LIFT4*.

constraint: The building has 3 floors ⟶ *LIFT5*

Fig. 8. The structured English of *LIFT5*.

event RequestFloor **guard**: a request at floor `f` is made ⟶ *LIFT6* **action**: new request is added to the pool of pending requests ⟶ *LIFT6*

Fig. 9. The structured English of requirement *LIFT6*.

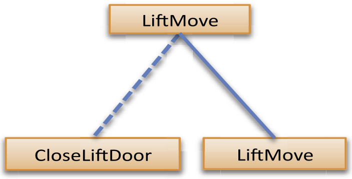


Fig. 10. The ERS diagram for *LIFT7*.

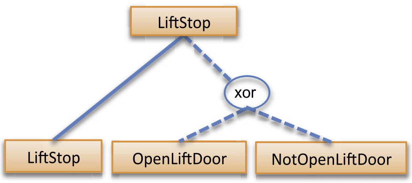


Fig. 11. The ERS diagram for *LIFT8*.

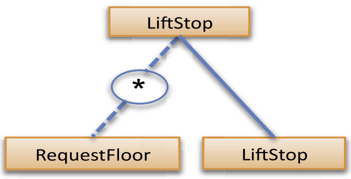


Fig. 12. The ERS diagram for *LIFT9*.

The flow requirements ***LIFT7***, ***LIFT8*** and ***LIFT9*** can be represented using the ERS diagrams in Figs. 10–12. Fig. 10 shows that the behaviour of the *LiftMove* event is realised by executing the *CloseLiftDoor* event followed by the *LiftMove* event. The xor-constructor pattern in Fig. 11 indicates that the behaviour of the *LiftStop* event in the root node is realised by executing the *LiftStop* event followed by either the *OpenLiftDoor* event or the *NotOpenLiftDoor* event. Finally, the behaviour of the *LiftStop* event in Fig. 12 is exhibited by executing the *RequestFloor* event multiple times followed by the *LiftStop* event. Note that the *LIFT9* requires one or more occurrences of the *RequestFloor* event whereas the ERS pattern in Fig. 12 allows zero or more occurrences. On Page 327 we show how the model is strengthened to address this.

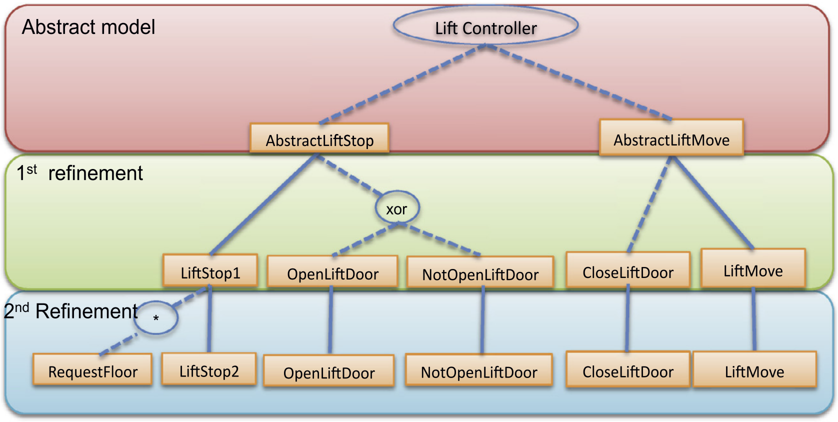


Fig. 13. The combined ERS diagrams for the lift controller.

3.2.2. Stage 2: Merging the structured English of a single event

It is possible that two or more structured English requirements refer to a single event. If such requirements exist, we merge them in the structured English. However, in this small lift case study we do not have requirements that refer to a single event. An example of this merging is given by the following two requirements:

TSK1	Tasks can be created and destroyed
TSK2	Tasks are assigned priority when created

TSK1 and *TSK2* are event-oriented requirements that refer to a *Task_Create* event. The structured English of these requirements are merged in this step.

3.2.3. Stage 3: Develop refinement strategy

Here we combine the ERS diagrams developed in the first stage in order to organise the refinement levels then we layer UML-B diagrams based on the combined ERS diagram. Flow is one criterion that can be considered in devising the refinement strategy. The nature of the requirements, the nature of the architecture that the refinement is aiming towards and the nature of the data types being refined are other important criteria that might come before the flow criterion since they may influence the flow requirements. The visualisation of the overall structure of the system gives more insight into the development of the refinement strategy before any Event-B modelling is carried out. It allows the developer to illustrate visually the hierarchy of the model based on the important criteria the developer is aiming at, and also helps to control the complexity of the model and view the number of events in each refinement level. Another advantage of the diagrammatic view of the refinement strategy is that it allows dependencies to be visualised. For example, in Event-B, events that update a particular variable should be introduced in the same modelling level. This is a restriction imposed by Event-B and is often only discovered during the modelling activity. The visual view of events given by the ERS diagrams helps to deal with this restriction before modelling. For instance, if the composed ERS includes two events: *addToA* and *RemoveFromA*. Both events must appear in the same refinement level of the composed ERS diagram. It is easy to notice this in the composed ERS diagram and it is important to put appropriate names for such events to make it easy to notice variable dependencies. Moreover, using this view, the developer can first introduce the basic properties of the system, and then introduce more complex properties that depend on the basic ones in the refinement levels. For instance, the developer of a real-time operating system (OS) can introduce basic properties of the processes used by the application developer in the abstract model, and complex properties that are used by the real-time OS to handle the processes in the refinement levels.

Fig. 13 shows the refinement levels for the lift controller case study.

In the abstract level, we decided to model two abstract events: *AbstractLiftStop* and *AbstractLiftMove*. We use a sequence pattern to indicate the sequencing between the abstract events. In the first refinement, we decided to combine the tree structure with root *AbstractLiftStop* that corresponds to the ERS diagram in Fig. 11 and the tree structure with root *AbstractLiftMove* that corresponds to the ERS diagram in Fig. 10. Finally, we use the ERS diagram in Fig. 12 to refine the *LiftStop1* event.

After organising refinement strategy then we layer UML-B diagrams based on the combined ERS diagram. This will facilitate integrating Event-B models generated from UML-B and Event-B models generated from ERS in Step 3. Fig. 14 shows the layered UML-B diagrams.

3.3. Step 3: Construct formal models

In stage 3, we organise the refinement levels and structure the hierarchy of the class diagrams according to the combined ERS diagram. In this step, we use the UML-B and ERS tools to convert the diagrams of step 2 to Event-B notation. We also

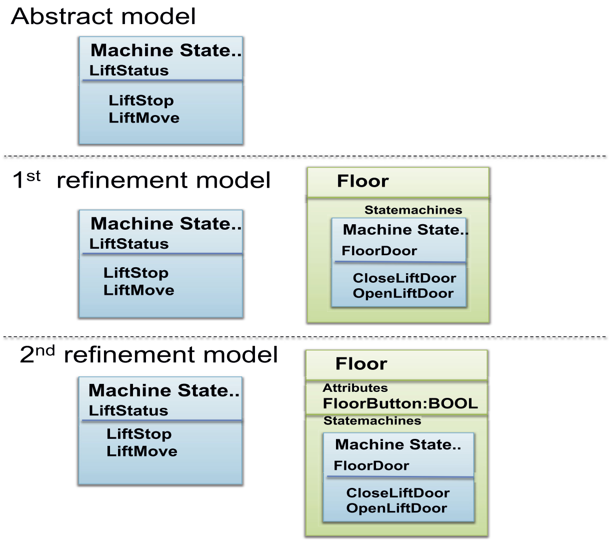


Fig. 14. Lift controller layered UML-B diagrams.

SETS
Floor_SET, *door_STATES*, *lift_STATES*
CONSTANTS
open
close
moving
stopped
AXIOMS
@open.type $open \in door\_STATES$
@close.type $close \in door\_STATES$
@distinctStates_door_STATES $partition(door\_STATES, \{open\}, \{close\})$
@distinctStates_lift_STATES $partition(lift\_STATES, \{moving\}, \{stopped\})$
End

Fig. 15. Sets, constants and axioms generated from the class and state machine diagrams.

manually convert the structured English representation of step 2 into Event-B. The Event-B model for the class and state machine diagrams are generated using UML-B since UML-B supports the refinement concepts. Each UML-B machine gives rise to both an Event-B context and an Event-B machine. Similarly, each ERS machine gives rise to an Event-B context and an Event-B machine. Thus, we have three contexts generated by the UML-B: *c0*, *c1* that sees *c0*, and *c2* that sees *c1*. We also have three machines generated by the UML-B, the abstract machine *m0*, the first machine *m1* that refines *m0*, and the second machine *m2* that refines *m1*. Similarly, the ERS gives rise to three contexts: *c0*, *c1* and *c3* and three machines: *m0*, *m1*, and *m2*.

This subsection presents examples of Event-B models generated by the UML-B and ERS tools, Event-B model corresponds to the structured English, and the process of integrating Event-B models generated by the UML-B and the ERS tools.

The Event-B specification of the semi-formal artefacts represented in Fig. 4, Fig. 5, and Fig. 6, that is generated from the class and state machine diagrams, is given in Fig. 15.

The **class and state machine diagrams** that represent **data-oriented requirements** are converted automatically into **sets, constants, axioms, variables, invariants, and events**. The Event-B model (Fig. 16) of state machines does not only show the states of the system. It also captures the events that specify how the variables can change. Fig. 4 contains a class represented by the variable *Floor*. This variable is defined as a subset of *Floor_SET*, which represents the set of all possible instances of *Floor*. *FloorButton* in Fig. 4 is translated into a function from *Floor* to *BOOL*. The state machine in Fig. 5 is translated into Event-B as disjoint sets representation as shown in axiom *@distinctstates_door_STATES*. States *open* and *close* are translated into constants of type *door_STATES*. Each transition is translated into an event whose guard specifies the source state and whose actions specify its target state. Hence, *OpenLiftDoor* is an event that changes the lift door from the *close* state to the *open* state and *CloseLiftDoor* is an event that changes the lift door from the *open* state to the *close* state. The state machine in Fig. 6 is translated in a manner similar to the state machine in Fig. 5.

The **structured English** that represents **constraint-oriented requirements** are converted into the appropriate Event-B elements: **invariants or axioms**. Invariants are predicates that specify constraints about the variables whereas axioms are predicates that specify constraints about the constants.

```
variables
Floor FloorButton door lift
invariants
Floor ∈ ℙ(Floor_SET)
FloorButton ∈ Floor → BOOL
door ∈ door_STATES
lift ∈ lift_STATES
```

```
event CloseLiftDoor
where
  door = open
then
  door := close
end
```

```
event OpenLiftDoor
where
  door = close
then
  door := open
end
```

```
event LiftMove
where
  lift = stopped
then
  lift := moving
end
```

```
event LiftStop
where
  lift = moving
then
  lift := stopped
end
```

Fig. 16. Variables, invariants and events generated from the class and state machine diagrams.

```
variables requests
invariants requests ⊆ Floor
events
  event RequestFloor
  any f
  where
    grd1 f ∈ Floor \ requests
  then
    act1 requests := requests ∪ {f}
  end
```

Fig. 17. The Event-B specification of the structured English of Fig. 9.

```
event RequestFloor
where
  LiftStop2 = FALSE
end
```

```
event LiftStop2 refines LiftStop1
where
  LiftStop2 = FALSE
then
  LiftStop2 = TRUE
end
```

Fig. 18. The Event-B specification generated for the ERS diagram (loop pattern) of Fig. 12.

The structured English of Fig. 7 specifies constraints about the position of the lift door and the lift motion which are variables and therefore, it is represented as the following invariant:

$$\boxed{lift = moving \implies door = close}$$

The structured English of Fig. 8 specifies assumptions about a constant (i.e. the number of floors). Therefore, it is represented as the following axioms:

$$\boxed{\begin{array}{l} MaxFloor = 3 \\ Floor = 0..MaxFloor \end{array}}$$

On the other hand, the **structured English** that represents **event-oriented requirements** are converted into **events**. Events are guarded actions specifying ways in which the variables can change. Sometimes, the variables of the constructed event are already defined in the model generated by the UML-B and the developer only needs to set those variables to appropriate values in the event actions. However, in some cases, the variables of an event might not exist in the model generated by the UML-B tool and therefore such variables need to be defined manually such as the case of the variable *requests* which is captured by the structured English of Fig. 9. (See Fig. 17.)

ERS diagrams that represent **flow-oriented requirements** are converted automatically to **variables, invariants, and events**.

The events generated from the ERS diagram of Fig. 12 are presented in Fig. 18.

According to the loop pattern rule, the *RequestFloor* event can be executed zero or more times before the execution of the *LiftStop* event. Thus, the *RequestFloor* event does not have a variable and an action to record the loop execution. It only has one guard $LiftStop2 = FALSE$ that allows zero executions of the loop event. We need to make a slight change to this pattern to allow the *RequestFloor* event to be executed at least one time before the execution of the *LiftStop* event. This can be achieved by manually adding a boolean flag *RequestFloor* together with the action $RequestFloor := TRUE$ in the *RequestFloor* event instead of the guard $LiftStop2 = FALSE$ in the *RequestFloor* event. Also we add the guard $RequestFloor = TRUE$ to the *LiftStop* event to check the execution of the *RequestFloor* event. That way, *RequestFloor* must be executed at least one time before the *LiftStop* event. This modification can be considered as a new repetition pattern that allows the execution of an event one or more times before the execution of other events. Clearly, there is a need to investigate further ERS patterns for different requirement types.

COMPOSED MACHINE *cm0*
INCLUDES
UML-B.m0
ERS.m0
INVARIANTS
$@UML-B.lift.type\ \ lift \in Lift\_STATES$
$@ERS.LiftMove.type\ \ LiftMove \in BOOL$
$@ERS.LiftStop.type\ \ LiftStop \in BOOL$
$@ERS.LiftStop\_Seq\ \ LiftStop = TRUE \Longrightarrow LiftMove = TRUE$
Events
LiftStop
Combines Events
$UMl - B.m0.LiftStop \parallel ERS.m0.AbstractLiftStop$
LiftMove
Combines Events
$UML - B.m0.LiftMove \parallel ERS.m0.AbstractLiftMove$
END

Fig. 19. The composed machine *cm* of UML-B.m0 and ERS.m0.

So far, we obtained two generated Event-B models: The first one is the model generated by the UML-B tool and the second one is the model generated by the ERS tool. The generated models can be combined using shared-event composition. Shared-event composition merges the variables and the invariants of each of the Event-B models. In each composed machine, events of the model generated by the UML-B are synchronised with events of the model generated by the ERS tool. Fig. 19 shows the composed machine *cm0* of *UML-B.m0*: the abstract machine generated by the UML-B tool and *ERS.m0*: the abstract machine generated by the ERS tool.

The composed machine *cm0* includes machines *UML-B.m0* and *ERS.m0*. Some invariants of *cm0* are generated in order to specify the type of variables. *@UML-B.lift.type* is type invariant of *lift* variable in *UML-B.m0* machine whereas *@ERS.LiftMove.type* and *@ERS.LiftStop.type* are type invariants of the control variables *LiftMove* and *LiftStop* in the *ERS.m0* machine. The invariant *@ERS.LiftStop_Seq* is an invariant in *ERS.m0* machine that maintains sequence ordering between *AbstractLiftStop* event and *AbstractLiftMove* event. Events of *cm0* are identified as the parallel composition (interaction) of *UML-B.m0* events: *LiftStop* and *LiftMove* and *ERS.m0* events: *AbstractLiftStop* and *AbstractLiftMove*.

3.4. Verification of Event-B models

The UML-B tool and the ERS tool generate Event-B models corresponding to UML-B and ERS developments, and some of the Event-B models that correspond to events and invariants are manually constructed. After the construction of Event-B models, the Rodin tool is then used for verification purposes. Rodin includes automatic tools to generate proof obligations associated with the generated Event-B models to ensure that the Event-B model is constructed correctly in a consistent manner [9]. Rodin also includes provers [9] that attempt to automatically discharge these obligations. Rodin generates proof obligations to verify well-definedness and invariant preservation as well as correctness of refinement steps. Each component in Event-B (variable, event, etc) has well-defined semantics. For example, $door \in door\_STATES$, where *door_STATES* is defined as: $partition(door\_STATES, \{open\}, \{close\})$, allows us to infer that door has only one of the two constant values *open* or *close*. Invariant preservation proof obligations ensures that events preserve invariants on the variables. The invariant will be true before the event is executed and must remain true when the event terminates. For example, the invariant:

$$lift = moving \Longrightarrow door = close$$

must be true before the *CloseLiftDoor* event is executed and must remain true when *CloseLiftDoor* event completes. This is guaranteed by the guards $CloseLiftDoor = False$ (guard generated by the ERS diagram of Fig. 11), $door = Open$, the invariant $door \in door\_STATES$, and the action $door := close$. For a refinement step to be valid, every possible execution of a refined machine must correspond to execution steps of its abstract machine. Gluing invariants are used to verify that the concrete machine is a correct refinement. For example, gluing invariants generated by the ERS tool give rise to proof obligations for abstract events and corresponding concrete events.

All the proof obligations for our models were generated and proved using the Rodin tool provers. The total number of proof obligations for the lift controller case study is 50 and all of them are discharged automatically.

The next section present the results of applying the proposed approach to a queue management case study.

4. The application of the proposed approach for constructing queue management model

This section shows the application of the proposed approach to construct an Event-B model of queue management from the requirements given in Table 3. The requirements presented in Table 3 have been collected from the FreeRTOS book and the FreeRTOS's source code [13,14]. FreeRTOS [13,14] is a mini real time kernel used for small embedded real time systems. In FreeRTOS, an application program consists of independent tasks. Queues are mechanisms used to serve task-to-task communication [14]. The collections of waiting tasks are used to store tasks that are waiting for messages.

Table 3
Data-oriented, Event-oriented, and Constraint-oriented requirements classification.

Label	Requirements	Classification
TSK1	Tasks can be created and deleted.	Event-oriented and Data-oriented
QUE1	Queues can be created and deleted.	Event-oriented and Data-oriented
TSK2	Only one task is running at a time.	Constraint-oriented and Data-oriented
TSK3	Tasks are assigned priority when created.	Event-oriented and Data-oriented
QUE2	A queue contains a limited number of items.	Constraint-oriented and Data-oriented
QUE3	A task can only send an item to a queue when there is enough room in the queue. Similarly, a task can only receive an item from a queue when the queue is not empty.	Event-oriented and Data-oriented
QUE4	The length of the queue is identified when the queue is created.	Data-oriented and Event-oriented
QUE5	Each queue has two collections of waiting tasks: tasks waiting to send and tasks waiting to receive.	Data-oriented
QUE6	A task that fails to send an item to a queue because the queue is full is placed into the collection of tasks waiting to send. Similarly, a task that fails to receive an item from a queue because the queue is empty are placed into the collection of tasks waiting to receive.	Event-oriented and Data-oriented
QUE7	Every task is mapped at most to one collections of waiting tasks.	Constraint-oriented and Data-oriented
QUE8	When a queue becomes available (there is an item in the queue to be received) then the highest priority task waiting for item to arrive on that queue (if any) will be removed from the collection of tasks waiting to receive.	Event-oriented and Data-oriented
QUE9	When a queue becomes available (there is room in the queue), then the highest priority task waiting to send item to that queue will be removed from the collection of tasks waiting to send.	Event-oriented and Data-oriented
QUE10	A queue should be locked before adding a send-failed task to the collection of tasks waiting to send. Similarly, a queue should be locked before adding the receive-failed task to the collection of tasks waiting to receive.	Event-oriented and Data-oriented
QUE11	Tasks that are blocked from receiving items from a queue will be unblocked when the required queue becomes non-empty. Similarly, tasks that are blocked from sending items to a queue will be unblocked when the required queue becomes non-full.	Event-oriented and Data-oriented
QUE12	Full queues that are locked are unlocked when all tasks waiting on that queue are unblocked.	Event-oriented and Data-oriented

The requirements describe several functions for queues such as creation of queues, sending messages on queues, receiving messages on queues, waiting for messages and an abstract description of locks which are used to prevent any task from modifying the collections of waiting tasks. In the following steps we apply the proposed approach to construct a queue management model from the requirements.

4.1. Step 1: Classify requirements

In order to classify the queue management requirements, we first classify the requirements based on data-oriented class, event-oriented class, and constraint-oriented class. After that, we classify the requirements based on flow-oriented requirements.

Table 3 categorises the queue management requirements based on data-oriented, event-oriented, and constraint-oriented classes.

Table 4 categorises the queue management requirements based on flow-oriented requirements.

In Table 4, we notice a connection between the requirements. Essentially they describe different cases. In *Flow1*, a task can either send an item to a queue successfully if the queue is available or fails to send that item, thus placing it into the tasks waiting to be sent. A similar scenario arise when a task attempts to receive an item from a queue. In *Flow2*, we notice a connection between the requirement *QUE3* and the requirement *QUE8*. When an item has been sent out successfully to a queue, the task waiting for that item will be unblocked (removed from task-waiting). Finally, *Flow3* shows a connection between the lock and unlock events. The queue will be locked when a task has failed to send or receive an item from a queue. The blocked tasks for that queue will unblock. Following that, the queue will be unlocked.

4.2. Step 2: Construct semi-formal artifacts and develop refinement strategy

4.2.1. Stage 1: Use semi-formal artifacts (UML-B, ERS, and structured English)

Due to space limitations, we present the semi-formal artifacts for some requirements which are *TSK1*, *TSK2*, *QUE3*, *QUE6*, *Flow1*, *Flow2*, and *Flow3* as follows.

Requirement *TSK1*

TSK1	Tasks can be created and deleted.	Event-oriented and Data-oriented.

Table 4
Flow oriented requirements classification.

Label	Requirements	Classification
QUE3	A task can only send an item to a queue when there is enough room in the queue. Similarly, a task can only receive an item from a queue when the queue is not empty.	*Flow1*
QUE6	A task that fails to send an item to a queue because the queue is full is placed into the collection of tasks waiting to send. Similarly, a task that fails to receive an item from a queue because the queue is empty is placed into the collection of tasks waiting to receive.	
QUE3	A task can only send an item to a queue when there is enough room in the queue. Similarly, a task can only receive an item from a queue when the queue is not empty.	*Flow2*
QUE8	When a queue becomes available (there is an item in the queue to be received) then the highest priority task waiting for item to arrive on that queue (if any) will be removed from the collection of tasks waiting to receive.	
QUE10	A queue should be locked before adding a send-failed task to the collection of tasks waiting to send. Similarly, a queue should be locked before adding the receive-failed task to the collection of tasks waiting to receive.	*Flow3*
QUE11	Tasks that are blocked from receiving items from a queue will be unblocked when the required queue becomes non-empty. Similarly, tasks that are blocked from sending items to a queue will be unblocked when the required queue becomes non-full.	
QUE12	Full queues that are locked are unlocked when all tasks waiting on that queue are unblocked.	

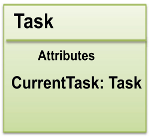


Fig. 20. The class diagram for *TSK1,2*.

The verbs *"created"* and *"deleted"* identify that *TSK1* requirement is of type event-oriented requirement, therefore, it is represented using structured English. Since *TSK1* is the first mention of the noun "Task", it introduces a data-oriented requirement. Therefore, tasks are represented using the class diagram shown in Fig. 20.

event : CreateTask
action: new task is added to the pool of tasks

event : DeleteTask
action: delete an existing task

Requirement *TSK2*

TSK2	Only one task is running at a time.	Constraint-oriented and Data-oriented.

TSK2 requirement is a type of constraint-oriented and data-oriented requirement, therefore, it is represented using structured English. *Running* task identifies an attribute of the task class introduced for *TSK2*, therefore we add the attribute *CurrentTask* to Task class to identify the running task as shown in Fig. 20.

Invariant: < Only one task is running at a time > $\longrightarrow$ <*TSK2*>

Requirement *QUE3*

QUE3	A task can only send an item to a queue when there is enough room in the queue. Similarly, a task can only receive an item from a queue when the queue is not empty.	Event-oriented and Data-oriented.

The verbs *"send"* and *"receive"* are identified as event-oriented requirements. Therefore, *QUE3* is represented as events using structured English representation. *"Queue item"* and *"task item"* identify the relationships between the nouns *"task"* and *"Queue"*, therefore, they are represented using the UML-B associations as shown in Fig. 21.

event: TaskQueueSend
guard: there is enough room in the queue
action: Task can send an item to a queue

event: TaskQueueReceive
guard: the queue is not empty
action: Task can receive an item from a queue

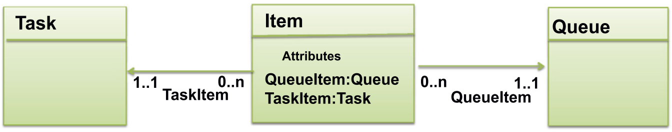


Fig. 21. The class diagrams for *QUE3*.

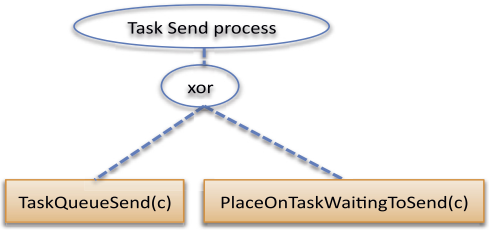


Fig. 22. ERS diagram for *Flow1*.

Requirement *QUE6*

QUE6	A task that fails to send an item to a queue because the queue is full is placed into the collection of tasks waiting to send. Similarly, a task that fails to receive an item from a queue because the queue is empty are placed into the collection of tasks waiting to receive.	Event-oriented and Data-oriented

QUE6 requirement is identified as an event-oriented requirement as it represents the action of placing tasks that have failed to send/receive to the collections of waiting-tasks. Therefore, *QUE6* is represented using structured English. The nouns *"tasks"*, *"queue"*, *"item"*, *"task waiting to send"*, and *"task waiting to receive"* classify *QUE6* as a data-oriented requirement. The class diagrams that represent these nouns are already given in Fig. 21.

event: PlaceOnTaskWaitingToSend
guard: the queue q is full
action: stores the task into the collection of tasks waiting to send an item to q

event: PlaceOnTaskWaitingToReceive
guard: the queue q is empty
action: stores the task into the collection of tasks waiting to receive an item from q

Requirement *Flow1*

QUE3	A task can only send an item to a queue when there is enough room in the queue. Similarly, a task can only receive an item from a queue when the queue is not empty.
QUE6	A task that fails to send an item to a queue because the queue is full is placed into the collection of tasks waiting to send. Similarly, a task that fails to receive an item from a queue because the queue is empty are placed into the collection of tasks waiting to receive.

FreeRTOS combines several functions and uses different structures such as branches and loops to manage the order of execution of these functions. Requirements *QUE3* and *QUE6* are an example of branching structure. A task can successfully send/receive an item to/from a queue if the queue is ready, otherwise the task is placed into the collection of waiting tasks. *QUE3* and *QUE6* are identified as conditional branching and therefore are represented using the "xor" ERS pattern. In this paper we focus on representing flows that describe sending-task process as shown in Fig. 22. The sending-task process has equivalent analogues as for the receiving-task process.

Requirement *Flow2*

QUE3	A task can only send an item to a queue when there is enough room in the queue. Similarly, a task can only receive an item from a queue when the queue is not empty.
QUE8	When a queue becomes available (there is an item in the queue to be received) then the highest priority task waiting for item to arrive on that queue (if any) will be removed from the collection of tasks waiting to receive.

QUE3 and *QUE8* requirements describe a sequence structure. The action of sending/receiving an item successfully to/from a queue, is followed by the action of removing the highest priority task waiting for that item.

QUE3 and *QUE8* requirements are identified as flow requirements and therefore are represented using an ERS sequence structure. The "sequence" pattern is used to represent the sequential structure as shown in Fig. 23. We also make use of the "xor" pattern to allow a task to be removed from the collection of tasks waiting to receive only if such a task exists. This is because it is possible that the collection of tasks waiting to receive is empty when a task successfully sends an item to a queue.

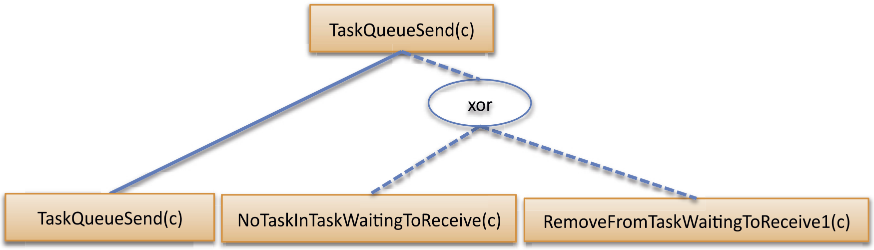


Fig. 23. ERS diagram for *Flow2*.

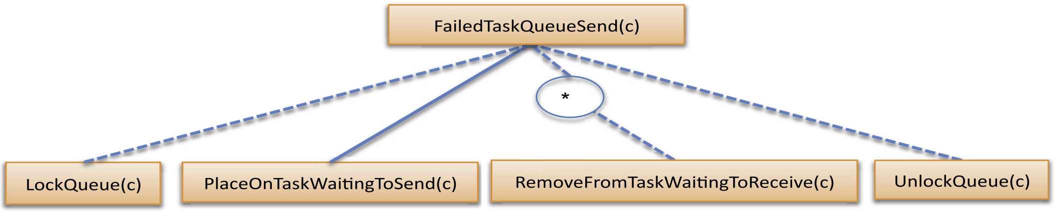


Fig. 24. ERS diagram for *Flow3*.

Requirement *Flow3*

QUE10	A queue should be locked before adding a send-failed task to the collection of tasks waiting to send. Similarly, a queue should be locked before adding the receive-failed task to the collection of tasks waiting to receive.
QUE11	Tasks that are blocked from receiving items from a queue will be unblocked when the required queue becomes non-empty. Similarly, tasks that are blocked from sending items to a queue will be unblocked when the required queue becomes non-full.
QUE12	Full queues that are locked are unlocked when all tasks waiting on that queue are unblocked.

QUE10,11 and *QUE12* requirements describe sequential ordering between the events: *LockQueue*, *PlaceOnTaskWaitingToSend*, *RemoveFromTaskWaitingToReceive*, and *UnLockQueue* when a task fails to send an item to queue as shown in Fig. 24.

4.2.2. Stage 2: Merging the structured English representation of a single event

This step merges the fragmented structured English that refers to a single event together. Grouping the fragmented structured English into a single structure, facilitates the process of translating the structured English representation into single events in stage 3.

The actions of *TSK1* and *TSK3* requirements are merged as follows:

event: CreateTask
action: new task is added to the pool of tasks
action: priority of a new task is set

4.2.3. Stage 3: Develop refinement strategy

In this step, we combine ERS diagrams and develop the refinement strategy. We aim to structure our development in a way that reflects the architecture of an embedded system. We also would like to keep flows of the ERS diagrams in Stage 1 unaffected as they reflect the execution order of FreeRTOS functions. The architecture of an embedded system consists of two main software layers which are the application layer (the uppermost layer) which defines the function and purpose of the embedded system and the RTOS layer which defines in detail how functions of the application layer are achieved. RTOS hides from application software, the hardware details of the processor upon which the application software will run. Therefore, in the abstract level we model the abstract *send* event that appears in the application level of FreeRTOS. In the first and the second refinement levels we add more details specific to the RTOS level including adding tasks that failed to send item to queue to the collection of tasks waiting to send and queues locking mechanisms. The abstract model includes the *TaskQueueSend* event and the *FailedTaskQueueSend* event (an abstract event of *PlaceOnTaskWaitingToSend* event). The introduction of the *FailedTaskQueueSend* event in the most abstract level reduces the complexity and allows us to defer the introduction of *PlaceOnTaskWaitingToSend* event, *RemoveFromTaskWaitingToSend* event, *PlaceOnTaskWaitingToReceive* event and *RemoveFromTaskWaitingToReceive* to the first refinement level. This is because these events are dependent on each other and therefore need to be defined in one modelling level. The atomicity of the *FailedTaskQueueSend* event is broken down into the first refinement level as *PlaceOnTaskWaitingToSend* event, *RemoveFromTaskWaitingToSend* event and *RemoveFromTaskWaitingToReceive* event.

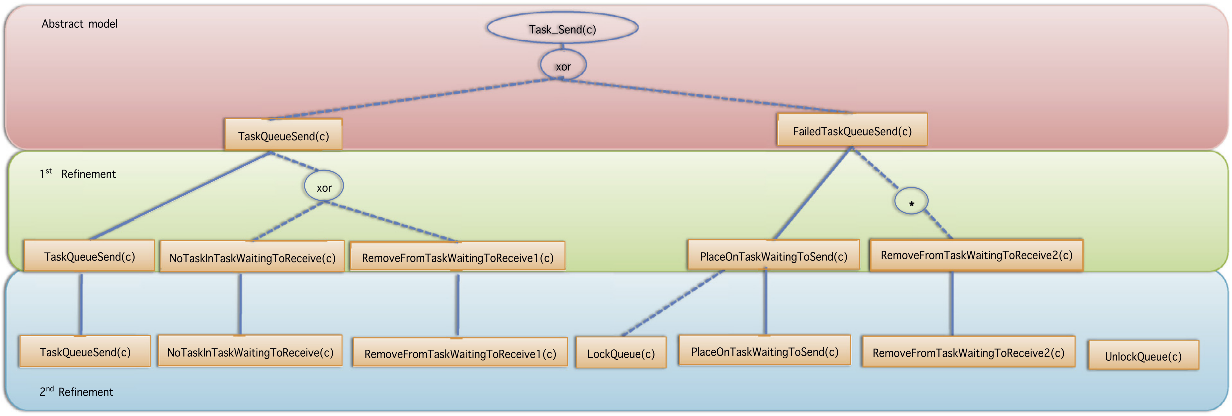


Fig. 25. The combined ERS diagram for task-send.

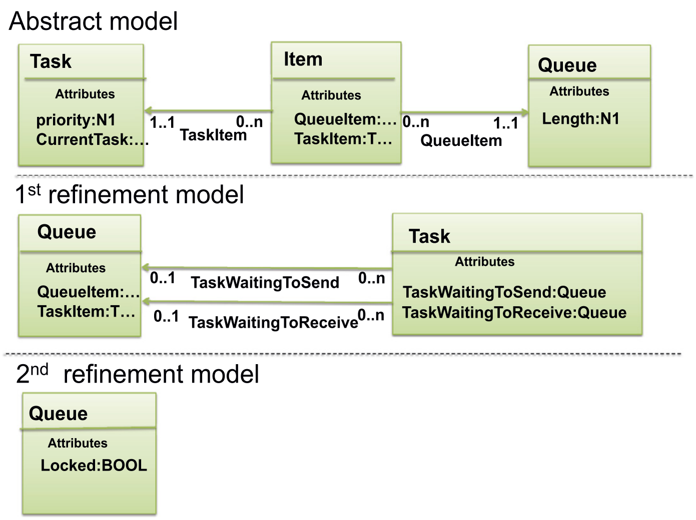


Fig. 26. Queue management layered class diagrams.

The most abstract level in Fig. 25 demonstrates task-send process. The tree with the root *Task_Send* corresponds to the ERS diagram shown in Fig. 22. The behaviour of the *Task_Send* process is realised by executing either the *TaskQueueSend* event when a task successfully sends an item to a queue or by executing the *FailedTaskQueueSend* event when a task fails to send an item to a queue.

In the first refinement level, the atomicity of *TaskQueueSend* which corresponds to the ERS diagram shown in Fig. 23 is broken down into three events. The abstract *TaskQueueSend* event is realised in the refinement by firstly executing the refinement *TaskQueueSend* event, then executing either *NoTaskInTaskWaitingToReceieve* event or *RemoveFromTaskWaitingToReceive1* event. Similarly, the abstract *FailedTaskQueueSend* event, which corresponds partially to the ERS diagram shown in Fig. 24, is realised in the refinement by firstly executing the *PlaceOnTaskWaitingToSend* event, followed by *RemoveFromTaskWaitingToReceive2* event for all the tasks placed on the *TaskWaitingToReceive*. In the second refinement level, the abstract *PlaceOnTaskWaitingToSend* event is realised by executing the *LockQueue* event followed by executing the *PlaceOnTaskWaitingToSend* event. *RemoveFromTaskWaitingToReceive2* event, on the other hand, is realised by firstly executing the *RemoveFromTaskWaitingToReceive2* event and then the *UnlockQueue* event.

The structure of the class diagrams that reflect the decided refinement strategy is shown in Fig. 26. The UML-B class diagrams are layered through the refinement based on the combined ERS diagrams of Fig. 25. Therefore, the abstract model specifies the abstract send/receive events. The first refinement specifies the collection of the waiting tasks and their events, whereas, the second refinement level specifies the queue lock mechanism.

4.3. Step 3: Construct formal models

In stage 3, we obtained three modelling levels in the combined ERS diagram and three modelling levels in the layered class diagrams. In this step we use the UML-B tool and the ERS tool to convert the resulted diagrams into Event-B

```
machine M1
refines M0
sees Cntxt
variables
  Task  Queue  TaskWaitingToSend  TaskWaitingToReceive
invariants
  @TaskWaitingToSend.type  TaskWaitingToSend ∈ Task ⇸ Queue
  @TaskWaitingToReceive.type  TaskWaitingToReceive ∈ Task ⇸ Queue
events  INITIALISATION
then
  @TaskWaitingToSend.init  TaskWaitingToSend := ∅
  @TaskWaitingToReceive.init  TaskWaitingToReceive := ∅
  end
end
```

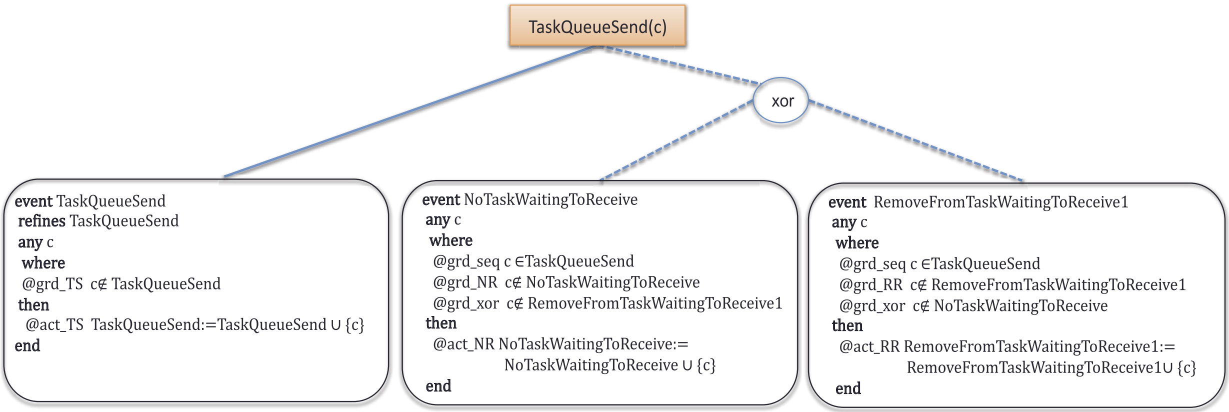
Fig. 27. Sets, constants and axioms generated from the class and state machine diagrams.

models and use shared-event composition to enable the integration of Event-B models. We show some parts of the models generated from class diagrams and ERS diagrams, as well as the model constructed from a structured English representation.

The Event-B model corresponds to the class diagrams shown in the first refinement of Fig. 26 is presented in Fig 27.

The Event-B model generated by the ERS tool that corresponds to *Flow2* is:

```
@inv_NR_seq  NoTaskWaitingToReceive ⊆ TaskQueueSend
@inv_RR_seq  RemoveFromTaskWaitingToReceive1 ⊆ TaskQueueSend
@inv_xor  partition((NoTaskWaitingToReceive ∪ RemoveFromTaskWaitingToReceive1),
          NoTaskWaitingToReceive, RemoveFromTaskWaitingToReceive1)
```



Each event corresponding to a leaf gives rise to a set control variable whose type is based on the type of the parameter *c* of the leaf, where *c* is of type *Task* (carrier set). Therefore, three set control variables are generated: *TaskQueueSend* set, *NoTaskWaitingToReceive* set, and *RemoveFromTaskWaitingToReceive1* set. The invariant labelled *@inv_xor* invariant ensures that at any time only one of the xor-constructor events can be executed. The *@inv_NR_seq* and *@inv_RR_seq* invariants ensure that *NoTaskWaitingToReceive* event and *RemoveFromTaskWaitingToReceive1* event can only executed after *TaskQueueSend* event.

@grd_NR in *NoTaskWaitingToReceive* event ensures that *NoTaskWaitingToReceive* event is executed after *TaskQueueSend* event. Similarly, *@grd_RR* in *RemoveFromTaskWaitingToReceive1* event ensures that *RemoveFromTaskWaitingToReceive1* event is executed after *TaskQueueSend* event. *@grd_xor* in *NoTaskWaitingToReceive* event and *@grd_xor* in *RemoveFromTaskWaiting-ToReceive1* event ensures that exactly one of these events executes in the sequence of *TaskQueueSend* event.

The Event-B model corresponds to the structured English of *PlaceOnTaskWaitingToSend* of *QUE6* is:

```
event  PlaceOnTaskWaitingToSend
refines  FailedTaskQueueSend
any  c q
where
  grd1  c ∈ CurrentTask
  grd2  q ∈ Queue
  grd3  Length(q) = card(QueueItem⁻¹[{q}])
then
  act1  TaskWaitingToSend := TaskWaitingToSend ∪ {q ↦ c}
end
```

The shared event composition tool is used to integrate Event-B models generated from UML-B diagrams and Event-B models generated from ERS diagrams. The Event-B components of the structured English are added manually to the composed machines. More detailed discussion about the integration steps of UML-B, ERS and refinement is given in Step 3 of Section 3.

All the proof obligations for our models were generated and proved using the Rodin provers. The total number of proof obligations for the queue management model is 116 and they are discharged automatically. At the beginning there were violation of some proof obligations due to some missing guards and actions. For instance, in the *DeleteQueue* event there was only one action corresponding to *TSK1* which was: $Queue := Queue \setminus \{q\}$. That action caused violation in the *DeleteQueue* event at the first refinement during the introduction of *QueueItem* variable. Rodin indicated that *DeleteQueue/QueueItem.type/INV* is the proof obligation that must be verified to show that the event *DeleteQueue* preserves the invariant (INV) with the label *QueueItem.type*. Thus, the action $QueueItem := QueueItem \lhd \{q\}$ was added to *DeleteQueue* event. After that amendment, the violated proof obligations of *DeleteQueue* event was discharged automatically.

5. Related work

This section presents some of the related work regarding the use of formal methods in operating systems and also some works in the area of requirements structuring and requirements traceability.

5.1. Formal development of operating systems

Craig's work is one of the fundamental sources in formal modelling of operating systems (OS) [15,16]. He focuses on the use of formal methods in OS development, and the work is introduced in two books. The first book is dedicated to specifying the common structures in operating system kernels in Z [17] and Object Z [18], with some CCS [19] (Calculus of Communicating Systems) process algebra used to describe the hardware operations. It starts with a simple kernel with few features and progresses on to more complex examples with more features. For example, the first specification introduced in the book is called a simple kernel, and involves features such as task creation and destruction, message queues and semaphore tables. However, it does not contain a clock process or memory management modules, whereas other specifications of swapping kernel contain more advanced features including a storage management mechanism, clock, interrupt service routines, etc.

The second of Craig's books [16] is devoted to the refinement of two kernels, a small kernel and a micro kernel for cryptographic applications. The books contain proofs written by hand, with some mistakes and some missing properties resulting due to manual proofs, some of which have been highlighted by Freitas [20].

Freitas [20,21] has used Craig's work to explore the mechanisation of the formal specification of several kernels constructed by Craig using Z/Eves theorem prover. This covers the mechanisation of the basic kernel components such as the process table, queue, and round robin scheduler in Z. The work contains an improvement of Craig's scheduler specification, adapting some parts of Craig's models and enhancing it by adding new properties. New general lemmas and preconditions are also added to aid the mechanisation of kernel scheduler and priority queue. Mistakes have been corrected in constraints and data types for the sake of making the proofs much easier, for instance, the enqueue operation in Craig's model preserves priority ordering, but it does not preserve FIFO ordering within elements with equal priority; this has been corrected by Freitas in [20].

Furthermore, Déharbe et al. [22] specify task management, queues, and semaphores in Classical B. The work specifies mutexes and adopts some fairness requirements to the scheduling specification. The formal model built was published in [23].

There is also an earlier effort by Neumann et al. [24] to formally specify PSOS (Provably Secure Operating System) using a language called SPECIAL (SPECIfication and Assertion Language) [25]. This language is based on the modelling approach of Hierarchical Development Methodology (HDM). In this approach, the system is decomposed into a hierarchy of abstract machines; a machine is further decomposed into modules, each module is specified using SPECIAL. Abstract implementation of the operations of each module are performed and then is transformed to efficient executable programmes. The work began in 1973 and the final design was presented in 1980 [24]. PSOS was focusing on the kernel design and it was unclear how much of it has been implemented [26]. Yet, there are other works inspired by the RSOS design such as Kernelized Secure Operating System (KSOS) [27] and the Logical Coprocessing Kernel (LOCK) [28].

The aforementioned examples follow a top–down formal method approach, where the specification is refined stepwise into the final product. On the other hand, there are also some earlier efforts in the area of formal specification and correctness proofs of kernels based on the bottom–up verification approach. The bottom–up approach adopts program verification methods to verify the implementation.

An example of this approach is a work by Walker et al. [29] on the formalisation of the UCLA Unix security kernel. The work is developed at the University of California at Los Angeles for the DEC PDP-11/45 computer. The kernel was implemented in Pascal due to its suitability for low-level system implementation and the clear formal semantics [30,31]. Four levels of specification for the security proof of the kernel were conducted. The specifications were ranging from Pascal code at the bottom to the top-level security properties. After that, the verification based on the first-order predicate calculus was applied that involves the proof of consistency of different levels of abstraction with each other. Yet, the verification was not completed for all components of the kernel.

Finally, there was an effort by Klein et al. [32,33] on the formal verification of the seL4 kernel starting with the abstract specification in higher-order logic, and finishing with its C implementation. The design approach is based on using the functional programming language Haskell [34] that provides an intermediate level that satisfies bottom–up and top–down approaches by providing a programming language for kernel developer and at the same time providing an artefact that can be automatically translated into the theorem prover. A formal model and C implementation are generated from seL4 prototype designed in Haskell. The verification in Isabelle/HOL [35] shows that the implementation conforms with the abstract specification.

5.2. Requirements structuring and requirements traceability

SOFL (Structured Object-Oriented Formal Language) [36] is an approach that uses graphical and textual formal notation for system construction. It is an integration of Data Flow Diagrams, Petri Nets, and VDM-SL to offer a visual and formal specification of a system. The graphical and textual formal notation serve as a good communication mechanism between a user and a developer. While our approach is supported by the UML-B tool and the ERS tool, SOFL is supported by a prototype of a tool for writing specifications of SOFL approach [37]. In addition, our approach provides requirements classification and offers guidance on which kind of semi-formal structure is used to model each requirement class. Similarly, the semi-formalisation process in SOFL method is carried out based on specific guidelines which are mentioned in [38].

Behaviour trees [39] are formal, graphical modelling language developed by Dromey to represent natural requirements [39]. Behaviour trees are of two forms: Requirement behaviour trees and Integrated behaviour trees. Requirement behaviour trees are used to graphically capture all functional behaviour in each individual natural language requirement. Integrated behaviour trees are used to compose all the individual requirement behaviour trees where every individual requirement is expressed as a behaviour tree and has a precondition associated with it. The integrated behaviour trees check that all preconditions are satisfied so defects can be discovered and corrected. The similarity between the behaviour trees and the use of ERS in our approach is that both approaches allow requirements to be expressed in detail and at an abstract level. The behaviour trees allow behaviour to be easily partitioned and separated out and the ERS allows the system to be visualised at different abstract levels. Behaviour trees and ERS diagrams are composable, however, behaviour trees can expose different behavioural defects such as aliases, inconsistencies, redundancies associated with the requirements information. Moreover, ERS can be translated into Event-B formal models and there is some work on linking a subset of behaviour trees to CSP [40].

Jastram et al. [41] present an approach to achieving requirement traceability. They structure the requirements based on WRSPM. WRSPM is a model used for the formalisation of system requirements. It differentiates between phenomena (state space and transitions of the system) and artifacts (the restriction on states and transitions). The artifacts are classified into groups: Domain Knowledge (W), Requirements (R), Specifications (S), Program (P) and Programming Platform (M). Once the requirements are structured using WRSPM, the second step is to use a formal model for system specification. WRSPM elements are mapped to Event-B. This mapping provides traceability between requirements and the Event-B model. They distinguish three types of possible traces: evolution traces, explicit traces, and implicit traces. Evolution traces are explored through the requirement evolution over time. Explicit traces are used to link each non-formal requirement to a formal statement. Implicit traces are discovered via refinement relationships, references to model elements or proof obligations. The main difference between our approach and [41] is that the latter focuses more on traceability and uses intermediate constructs based on WRSPM to provide traceability between requirements and Event-B models. On the other hand, the intermediate constructs which we use are based on a requirement classification derived from Event-B components. As a result, the process of converting the semi-formal artifacts into an Event-B model is straightforward.

Yeganefard and Butler [42] describe an approach for structuring requirements of control systems to facilitate refinement-based formalisation. The approach has three stages: In the first stage, requirements are categorised into monitored (MNR) requirements, commanded (CMN) requirements and controlled (CNT) requirements. The second step involves layering requirements by modelling one feature in each refinement level; the developer chooses which feature to model in each refinement level. The authors suggest modelling the main role of the system with a minimum set of requirements in the very abstract model. The third step is based on revising the requirement document and the formal model to investigate any inconsistent, ambiguous or missing requirements. Comparing our work with [42], the approach used in [42] is specific to control systems whereas the approach of this paper is based on Event-B structures. We also think that structuring refinement levels based on a textual requirement document is difficult. We believe that the visualisation of Event-B components using ERS diagrams gives a clear overview of the whole system and helps decide which feature to model in each refinement level. It should be possible to combine our approach with that of [42] to obtain more effective guidelines for developing traceable Event-B models for control systems.

KAOS and i* are goal-oriented requirement engineering methods that specify the high level goals of the system. A goal is a statement of a system whose satisfaction is determined by the cooperation of the agents of the system such as humans, devices, etc. Goals drive requirement details which leads to domain-specific requirements that could be implemented. Goals may be organised in an AND-refinement hierarchy [43]. The higher-level goals are strategic and coarse-grained whereas lower-level goals are technical and fine-grained. In our work we used ERS to structure the behaviour of the models. ERS patterns are used to manage the execution between events whereas KAOS is used to structure requirement goals. Some work, however, have been done to generate high-level Event-B system from KAOS requirements and there is a tool support that links KAOS/Objectiver tool and the Event-B/Rodin tools [44].

6. Conclusions and future work

We have described an approach which facilitates constructing Event-B models via semi-formal requirements structures and provides clear traceability between requirements and the Event-B model. The approach is based on the use of the UML-B and ERS approaches. UML-B provides UML-like graphical modelling that allows the development of an Event-B model, whereas the ERS approach provides a graphical notation to structure refinement and manage flows in an Event-B model.

Applying UML-B at the requirement level facilitates the mapping from data-oriented requirements to Event-B. Event-B models of the UML-B diagrams are generated automatically by the UML-B tool. On the other hand, applying the ERS approach at the requirement level assists a developer in the process of deciding which features to be modelled in each refinement step. Moreover, part of the Event-B model is generated automatically by the ERS tool, which reduces the burden of the manual work especially in the development of complex systems. The combined ERS diagrams provide an overall visualisation of the refinement structure and demonstrate the relationships between events even before any model is written.

From the application of our approach to the queue management case study, four conclusions were drawn: Firstly, we found that most of the requirements were classifiable according to the classification scheme. Several requirements can be classified as event/constraint and data oriented requirements such as *TSK3*, *QUE4*, and *QUE7*. It is possible to define clearly data-oriented requirement and separate them from event/constraint-oriented requirements. We can consider that data-oriented requirement only describe attributes of the system, constraint-oriented requirements describe properties about the system and event-oriented requirements describe the activities of the system. Then, we ignore all the nouns and attributes mentioned in the constraint/event-oriented requirements. Therefore, *TSK3* can be restructured as follows:

TSK3-1	Each task has a priority associated with it.
TSK3-2	Tasks are assigned priority when created.

In the above formulation, *TSK3-1* is a data-oriented requirement whereas *TSK3-2* is an event-oriented requirement. In *TSK3-2*, we only focus on the action of assigning a task priority when created, and thus consider *TSK3-2* as an event-oriented requirement. We regard priority as an attribute of a task in *TSK3-1* and classify *TSK3-1* as a data-oriented requirement. Secondly, we found that the flow requirements can sometimes be extracted from more than one requirement as shown in Table 4. Thirdly, ERS patterns do not cover all possible flows; we sometimes need to modify them to represent the exact flow we are looking for, or even explore some new patterns. For example, one might need to represent "one or more" executions of an event. This is currently not supported by the existing patterns, however, the loop ERS pattern together with an additional manual flag can be used to represent this particular case. Finally, it is possible that a particular event becomes a leaf in different ERS diagrams. In some cases however, it is necessary to change the name of the repeated leaf to avoid an invalid combination of ERS flags. Assume that an event x is a leaf in a sequence diagram and also a leaf in an "xor" diagram. If this leaf has the same name in both trees, then the ERS tool will generate "xor" flags and sequence flags for the event x. Mixing flags together in a single event can result in mis-behaviour of the intended flows. Overall, further investigations should be considered to evaluate the composition of ERS diagrams and to explore more useful patterns for managing the flows.

The application of the proposed approach to several case studies is the primary goal of future work. In this paper we have described one kind of constraint-oriented requirements, namely requirements on the system being developed, such as requirement *LIFT4*. We also need to investigate another type of constraint-oriented requirements, which describe assumptions on the environment, such as the following requirement:

LIFT10	The lift can transition from stopped to moving-up or moving-down, from moving-up or moving-down to stopped, but not from moving-up to moving-down or vice versa

Exploring the scalability of the graphical models is another direction for future work. The visual view of the refinement strategy provides some support for scalability: the ERS diagrams are hierarchical and it is always possible to partition the diagram into sub-hierarchies; UML-B class diagrams can also be layered through refinement. Further work is needed to investigate the issue of scalability. Finally, further investigation of several ERS patterns is necessary to support a larger class of flow requirements.

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