Lessons Learned/Sharing the Experience of Developing a Metro System Case Study

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Abstract. In this document we share the experiences gained throughout the development of a metro system case study. The model is constructed in Event-B using its respective tool set, the Rodin platform. Starting from requirements, adding more details to the model in a stepwise manner through refinement, we identify some keys points and available plug-ins necessary for modelling large systems (requirement engineering, decomposition, generic instantiation, among others), which ones are lacking plus strengths and weaknesses of the tool.

Keywords: Event-B, Rodin, requirements, refinement, decomposition, generic instantiation

1 Introduction

Event-B [1] is a formal method that allows modelling and refinement of systems. From the experiences during DEPLOY\(^1\), there exists a natural instinct to model a system such that it mimics its implementation. That is not always the best approach: models should be used to understand the system and its behaviour; the implementation should be seen as an independent task. This document aims to guide modellers by describing the experiences gained throughout the development of a metro system case study, suggesting “rules of thumb”, modelling techniques and assessing the current tool support (Rodin platform [2]).

We build a metro system model in a “top-down” style, in Event-B based on safety properties, starting from an abstraction view of the system and gradually augmented it with more details. Generic instantiation [3,4,5] and decomposition [6] are techniques used in the case study, simplifying the formal development by reusing existing models and avoiding re-proofs. Some requirements are based on real ones for metro system carriage doors.

A brief overview of the Event-B language is given in Section 2. The construction of the metro system model is described in Section 3, including a discussion of the keys points for building of a formal model such as requirements, abstraction, refinement, proofs, decomposition, generic instantiation in the Rodin platform. We finish with conclusions and related work in Section 4.

\(^1\) DEPLOY - Industrial deployment of system engineering methods providing high dependability and productivity - supported by the EU Commission (Grant 214158)
2 Background

Event-B is a formal modelling method for developing correct-by-construction hardware and software systems. An Event-B specification is divided into two parts: a static part called context and a dynamic part called machine. A machine SEES as many contexts as desired. A context consists of sets, constants and assumptions (axioms) of the system. An Event-B model is a state transition system where the state corresponds to variables $v$ and transitions are represented by a collection of events $\text{evt}$ in machines. The most general form of an event is: $\text{evt} \triangleq \text{any } t \text{ where } G(t, v) \text{ then } S(t, v, v') \text{ end}$, where $t$ is a set of parameters, $G(t, v)$ is the enabling condition (called guard) and $S(t, v, v')$ is a before-after predicate computing after state $v'$. Essential to Event-B is the formulation of invariants $I(v)$: safety conditions/properties to be preserved at all times. Proof obligations (PO) are generated for all system transitions to validate and ensure that these conditions are preserved. Because Event-B advocates the use of refinement, additional PO (forward refinement) \cite{1} are generated to ensure that concrete refinements preserve the abstract models’ properties. The Event-B toolset is Rodin \cite{2}, result of an EU research project\footnote{RODIN:Rigorous Open Development Environment for Open Systems (EU IST Proj)}: software tool, based on modern software programming tools created to help the development of specifications based on the idea that large complex or critical projects should start with modelling and reasoning about its specification.

3 Case study construction

In this section the steps followed throughout the construction of our model are described. The safety-critical metro system case study describes a formal approach for the development of embedded controllers for a metro\footnote{The Event-B model built is available at \url{http://eprints.ecs.soton.ac.uk/23135/}}. Butler \cite{7} makes a description of embedded controllers for a railway using classical B. Our starting point is based on that work but applied to a metro system. That work goes as far as our first decomposition. We augment it by refining sub-components, adding requirements and instantiating emergency and service doors in carriages.

3.1 Requirements

Requirements analysis \cite{8} in systems engineering, encompasses tasks that go into determining the needs or conditions to meet for a new or altered product, taking account possible conflicting requirements of the various stakeholders, such as beneficiaries or users. There are several techniques to deal with requirements and they vary according to projects’ domains. Moreover guidelines \cite{8} have been developed to achieve this goal. Nevertheless requirements are often described in an informal manner. Consequently it is hard to reason about each requirement: experienced people are able to detect contradictions and uncertainties but it is not
guaranteed that all will be uncovered. Moreover, within the formal methods domain, it is hard to trace informal requirements with the model/implementation.

Although not available when we developed this case study, a requirement plug-in (ProR [9,10]) now exists for the Rodin platform, supporting ReqIF 1.0.1 Standard. Benefits of ProR are incremental creation of hierarchical requirements structures from informal requirements or providing traceability between requirements and formal models. Furthermore, the system description, mixing formal and informal artefacts may contain assumptions about the environment or requirements properties and ProR can reason about them (possibly uncovering contradictions and uncertainties).

Our metro system is characterised by trains, tracks circuits (also called sections or CDV and a communication entity (comms) that allows the interaction between trains and tracks. The trains circulate in sections and before a train enters or leaves a section, a permission notification must be received. In case of hazard situations, trains receive braking notifications. Track is responsible for controlling the sections, changing switch directions (switch is a special section that connects different routes and can be either divergent or convergent) and sending signalling messages to the communication entity. These are the main requirements for this case study (some described in Fig. 1):

1. Route sections are all connected and cannot have empty gaps (inv1).
2. There are no loops in the route sections: sections cannot introduce loops (thm3). Moreover no circularity is allowed (via transitive closure: thm4).
3. Switches cannot be connected and can be either divergence or convergent.
4. Non-switches have at most one successor and at most one predecessor section.
5. Trains circulate in tracks (inv4, inv5, inv7), preserving transitive closure.
6. Trains occupy at least one section plus a safety distance (inv4).
7. Trains cannot be in the same section at the same time (trains crashed: inv13).
8. Comms handles messages exchanged between trains and tracks. Trains heading to an occupied section receive a negative access and braking message.
9. As part of the safety requirements, all trains have an emergency button.
10. While the emergency button is enabled, the train cannot speed up (braking).
11. If a train door is opened, then the train is stopped (in a platform or due to an emergency). In contrast, if the train is moving, then its doors are closed.

3.2 Abstraction

Following a “top-down” design, the development starts with an abstraction model: description that encompasses the main aspects and goals the system intends to answer, obstructing itself from the implementation and other details. Getting a good abstraction is a very hard task requiring an accurate understanding of the system. Moreover the abstraction is the basis of the development playing a crucial role in the entire model. A good abstraction is often not achieved at first attempt even for experienced developers. It may change throughout the

\footnote{ReqIF: Requirements Interchange Format - \url{http://www.omg.org/spec/ReqIF/}}
development to fit additional requirements that came into play on a later stage or when, after a few refinements, it does not fit exactly as initially desired. No tools are available that help finding the right abstraction mainly because each system has its specific properties. It often relies on experience and empirical research. Nevertheless we believe that systems can be categorised according to some common properties, architecture and behaviours and therefore having a abstraction template repository could be helpful when starting a model development. Abstraction templates could then be customised according to specific needs. Unfortunately such repository does not yet exist, requiring further investigation beyond the scope of this paper.

For our abstraction model (Fig. 1), we focus on the main properties: tracks are divided into sections that are connected (Reqs. 1, 2, 3, 4); trains circulate in tracks (Req. 5); the most important (safety) global property introduced initially states that trains cannot be in the same section at the same time (Reqs. 6, 7).

Fig. 1. Excerpt of MetroSystem_M0: variables and invariants

3.3 Refinement

Refinement allows the construction of a model in a gradual way, making it closer to an implementation [3]. At same time, the overall correctness of the system is preserved. Our case study heavily uses refinement as seen in Fig. 2. At each refinement step, new requirements are introduced to the model and consequently new invariants, variables, events are introduced or refined. For instance, for refinement Train_M1, the invariants and properties imposed are:

1. There is a limit to the number of carriages per train.
2. If a carriage alarm is activated, the train’s emergency button is also active.
3. The sum of carriage doors corresponds to the doors of a train.
4. Trains have states: maintenance, manual, automatic.
5. If a train is not in a maintenance state, then it must have the correct number of carriages and the leader carriage must be defined already.
6. If a train is in maintenance, then it must be stopped.
7. The emergency brake is activated if a train exceeds the maximum speed.

Do it right at first/Recursion As for abstraction, refinement steps are not reached at first attempt. They evolve, accommodate different requirements and also change, impacting previous refinements. And that comes with a cost: a change in the abstraction, affects all the following refinements and the adjustment to each refinement level has to be done manually, which is cumbersome. In our case, the emergency brake requirement (Req. 9) was only added after we had reached the first decomposition. The consequences propagated to the abstraction, impacting most events and manual reprov (which delayed for a few days the progress achieved before). This is a limitation of the refinement process in the tool that does not propagate the changes, requiring improvements.

3.4 Proofs and model construction
Proofs play an important role in formal modelling, checking that properties and behaviours are preserved. There is always a compromise between representing a system, avoiding complex proofs and tool limitations. Despite the plug-ins available for automated proof solving (AtelierB provers [11], Relevance Filter [12]), complex proofs tend to be avoided. From our experience, a complex proof hard (but not impossible) to discharge, often means that the model is overcomplicated and may be rewritten/simplified. When building Train_M2, train doors were represented as \((DOOR \rightarrow CARRIAGE; train\_carriage)^{-1}\), where \(DOOR\rightarrow CARRIAGE\) represents carriage doors and \(train\_carriage \in CARRIAGE\rightarrow trns\) represents the train carriages. Although that relation is enough to describe which doors are part of a train, from a proof viewpoint was very unsuccessful. By rewriting train doors as variable \(door\_train\_carriage = (DOOR\rightarrow CARRIAGE; train\_carriage)^{-1}\) and invariants \(door\_train\_carriage \in trns \leftrightarrow DOOR, door\_train\_carriage^{-1} \in DOOR \rightarrow trns\), we solved the issue.

From a tool viewpoint, there is a direct relation between the number of PO per refinement and performance. Our criteria to choose which properties to add per refinement were directly related with the PO generated per refinement: if over 150 PO, additional properties were stated in new refinements. Train requirements are spread over 4 refinement steps for that reason. Improvements have been made in terms of tool performance in the latest releases but large developments (over 15 refinements and large number of events) are still affected.

3.5 Decomposition
The “top-down” style of development used in Event-B allows the introduction of new events and data-refinement of variables during refinement steps. A consequence of this development style is an increasing complexity of the refinement
process when dealing with many events and state variables. Model decomposition [6] addresses such complexity by cutting a large model into smaller components. Two methods have been identified for the Event-B decomposition and are supported by a Rodin plug-in [6]: shared variable [3] and shared event [13]. Because decomposition is monotonic [13], the generated sub-components can be further refined independently: sub-components can be used to further refined the original model or be used in other models. Moreover, team development can be introduced: different developers can share parts of the same original model by working independently in parallel with the resulting decomposition sub-components. Decomposition also partition PO which are expected to be easier to discharge in sub-components. In our model, decomposition is used for following reasons: separation of aspects; model architectural decision; tool performance: building/proving is faster for separated models than for monolithics.

Decomposition is recursively used as seen in Fig. 2: splitting the initial monolithic model into three parts (Train, Middleware and Track) from an architectural point of view (separation of aspects); splitting Train_M4 into Leader-Carriage (due to the number of POs and separation of aspects) and Carriage and later on to decompose Carriage into CarriageInterface and CarriageDoor (Fig. 3(b)). Although we could have used either decomposition styles, we used the shared event style mainly because in that manner, we did not constrain the refinement of variables (like it happens for shared variables).

Unfortunately the decomposition process does not propagate modifications on the original machine and consequently, decomposed components need to be regenerated if the original component is modified. If the decomposed components have been refined, then the modifications need to be reflected in those refinements (notified via errors or PO being generated or requiring re-proving). We believe that the decomposition tool requires improvements in terms of propagation changes to minimise the overall impact that is inevitable.

![Fig. 2. Overall view of the metro system development](image-url)
3.6 Generic Instantiation

Generic Instantiation can be seen as a way of reusing components and solving difficulties raised by the construction of large and complex models [3]. Generic developments (single machine or a chain of refinements) are reused, originating components with similar properties instead of starting from scratch. Reusability occurs via the instantiation and parameterisation of patterns. [4] proposes a generic instantiation approach for Event-B by instantiating machines. The goal is to reuse a pattern as an instance in an existing development (problem) consisting of a chain of refinement of machines $S_0$ to $S_k$ ($S$ stands for Specific problem) as seen in Fig. 3(a). The instance sees the parameterisation context $C_{IG}$ (that extends the specific problem context $C_S$) containing the replacement properties for the elements in context $C_{Gi}$. Variables, events and parameters can be renamed to fit new or existing elements in the specific problem. The correctness of the instantiation relies on reusing the pattern PO and ensuring that assumptions in the context parameterisation are satisfied in the instance. In our case study, an existing development of carriage doors ($GCDoor_M0..GCDoor_M2$) is used as a pattern with all the related PO previously discharged. The pattern is instantiated and parameterised accordingly into emergency doors and service doors (Fig. 3(b)). The main pattern requirements are:

1. Doors have a state associated: open (train must be stopped) or closed.
2. When adding/removing a carriage to a train, doors must be closed for safety.
3. Actions involving the doors may result from commands (open, close, isolate, remove_isolated) sent from the central door control.
4. Doors must be closed and locked before a train starts moving.
5. Doors are opened by the following devices: manual, platform, manual internal or automatic central door.

6. Doors can get obstructed when closed automatically (people/object obstruction). If an obstruction is detected, a second attempt is made to close them.

7. Doors can be isolated in case of malfunction or for safety reasons.

8. If a door is obstructed, then it must be in a state corresponding to open.

These requirements are shared between both emergency and service doors highlighting the use of instantiation. Additional requirements for each kind of door can be added in further refinements (emergency doors are only available for emergencies, do not respond to standard open command, etc). For our case, the instantiation was manual. Nevertheless currently a generic instantiation prototype is available. The tool needs to mature and requires improvements in terms of matching the pattern and the last refinement of problem. In this case study, the matching was manually achieved through decomposition.

**Animation/Model Checker and Code Generation** Although we are mainly interested in safety properties, ProB model checker proved to be a very useful tool. At some stages, all PO were discharged but ProB showed that the system was deadlocked. In larger developments, these situations may occur frequently. Therefore we suggest safety properties preservation (via PO) and running ProB to confirm deadlock freeness. Another option, to be addressed by ADVANCE is to introduce liveliness properties (e.g. enabledness). Regarding implementation, a code generation plug-in [6] (Event-B to Ada or C) is available.

**Statistics** Table 1 describes the statistics of the model in terms of variables, events and PO (including automatically discharged) for each refinement. Almost 3/4 of the PO were discharged automatically. The case study conditions

| Vars | Events | PO/Auto |
|------|--------|---------|
| TransitiveClosureCtx | - - | 10/10 |
| MetroSystem_C0 | - - | 5/3 |
| MetroSystem_C1 | - - | 0/9 |
| MetroSystem_M0 | 7 10 | 75/64 |
| MetroSystem_M1 | 10 13 | 17/17 |
| MetroSystem_M2 | 12 17 | 78/57 |
| MetroSystem_M3 | 12 15 | 44/22 |
| Track | 4 10 | 0/0 |
| Train | 7 14 | 0/0 |
| Middleware | 1 4 | 0/0 |
| Train_M1 | 9 10 | 74/24 |
| Train_M2 | 13 21 | 155/79 |

**Table 1.** Statistics of the metro system case study

5 ADVANCE project: Advanced Design and Verification Environment for Cyber-physical System Engineering- http://www.advance-ict.eu/

6 Code generation plug-in: http://wiki.event-b.org/index.php/Code_Generation
were the following: Rodin v2.1 (Auto Builder: OFF; Auto Prover: OFF), Model Decomposition v1.2.1 and Shared Event Composition plug-in v1.3.1. Generic instantiation was done manually (tool support was not available), ProB v2.1.2.

4 Related Work and Conclusions

From the experience of developing formal models involving a large number of refinements, development tools reach a saturation point where it is not possible to edit the model due to the high amount of resources required (or very slowly). Decomposition is a possible solution that alleviates the issue by splitting the model into tool manageable dimensions, separating concerns, decreasing the number of events and variables per sub-component which results in more manageable models. Generic instantiation reuses pattern and respective PO per instance.

The experience of modelling a metro system in Event-B using the Rodin platform and its plugins, is shared in terms of model design and assessment of available tools. Requirements are defined and modelled through refinement. As an architectural decision and to alleviate the problem of modelling a monolithic component, the model is decomposed several times. Benefiting from an existing development for carriage doors GCDoor, this pattern is used to instantiate two kind of carriage doors: service and emergency doors. The refinement of Carriage is decomposed, originating CarriageDoor that matches with pattern GCDoor M0. Although the instantiation is similar for both cases, the resulting instances can be further refined independently. Generic instantiation minimises the proving effort reusing the pattern GCDoor PO (in the overall 257). Therefore we achieve our goal of reusing existing developments and discharging as little PO as possible. Even the interactive proofs were relatively easy to discharge once the correct tactic was discovered. This task would be more difficult without decomposition due to the elevated number of hypotheses to be considered. Nevertheless the effort of discharging PO could be further minimised by having an easy way to reuse PO tactics. A limitation of this model is not addressing liveness properties through proofs which would enrich the model.

Although we use Event-B, these techniques are generic enough to suit other formal notations and other case studies. Formal methods has been widely used to validate requirements of real systems. The systems are formally described and properties are checked to be preserved whenever a system transition occurs. Usually this result in complex models with several properties to be preserved, therefore structuring and reusability are pursued to facilitate the development. Lutz [16] describes the reuse of formal methods when analysing the requirements and designing the software between two spacecrafts’ formal models. Stepney et al. [17] propose patterns to be applied to formal methods in system engineering. Using the Z notation, several patterns (and anti-patterns) are identified and catalogued to fit particular kind of models. These patterns introduce structure to the models and aim to aid formal model developers to choose the best approach to model a system, using some examples. Although the patterns are expressed for Z, they are generic enough to be applied to other notations. Comparing with
the development of our case study, the instantiation of service and emergency doors corresponds to the Z promotion, where a global system is specified in terms of multiple instances of local states and operations. Although there is not an explicit separation of local and global states in our case study, service and emergency doors states are connected to the state of CarriageDoor and we even use decomposition, instantiation and refactoring to fit into a specific pattern. Stepney [17] suggests template support and architecture patterns to be supported by tools. We agree and aim to address this issue in the future by having categorised templates customised according to the modeller’s needs.

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