

Testing Quick Reference Handbooks in Flight Simulators

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Preface

Abstract

This is an abstract.

Declaration

I declare that this dissertation represents my own work except where otherwise stated.

Acknowledgements

This is the acknowledgements.

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Chapter 1

Introduction

1.1 Scene

- Designing Emergency Checklists is difficult
- Procedures in checklists must be tested in simulators [1], which usually means trained pilots test it, as the tests need to work consistently [2] (making sure it's not lengthy, concise and gets critical procedures)
- Checklists are usually carried out in high workload environments, especially emergency ones

1.2 Motivation

- Testing procedures in checklists are often neglected [1]
- There are some checklists that may not be fit for certain scenarios - e.g. ditching (water landing) checklist for US Airways Flight 1549 assumed at least one engine was running [3], but in this scenario, there were none
- Some checklists may make pilots 'stuck' - not widely implemented, could be fixed with 'opt out' points. e.g. US Airways 1549, plane below 3000ft, could have skip to later in the checklist to something like turn on APU, otherwise plane will have limited control [3].
- Checklists may take too long to carry out - Swissair 111

1.3 Aim

The goal of this project is to test checklists in Quick Reference Handbooks (QRH) for flaws that could compromise the aircraft and making sure that the tests can be completed in a reasonable amount of time by pilots. It is also crucial to make sure that the tests are reproducible in the same flight conditions and a variety of flight conditions.

1.4 Objectives

1. Research current checklists that may be problematic and are testable in the QRH tester being made
2. Implement a formal model that runs through checklists, with the research gathered to produce an accurate test
 - (a) Understand the relative states of the aircraft that need to be captured
 - (b) Ensure that the results of the checklist procedures are consistent
3. Implement a QRH tester manager that
 - Runs the formal model and reacts to the output of the formal model

- Connect to a flight simulator to run actions from the formal model
- Implement checklist procedures to be tested, run them, and get feedback on how well the procedure ran

Chapter 2

Background

2.1 Hypothesis

- Checklists can be tested in a simulated environment to find flaws in checklist for things like
 - Can be done in an amount of time that will not endanger aircraft
 - Provides reproducible results
 - Procedures will not endanger aircraft or crew further (Crew referring to Checklist Manifesto with the cargo door blowout)
- Results in being able to see where to improve checklists

2.2 Safety in Aviation

2.2.1 History

- 70-80% of aviation accidents are attributed to human factors [4]

2.2.2 Checklists

- Checklists have been shown to aid in minimising human errors [2]
- However, checklists can be misleading and compromise the safety of the aircraft due to them being either too confusing or taking too long to complete [1]
- That is why testing checklists are important to avoid these situations

2.3 Formal Methods

2.3.1 History

2.3.2 Application

2.4 Solution Stack

- There would be around 3 main components to this tester
 - Formal Model
 - Flight Simulator plugin
 - Checklist Tester (to connect the formal model and flight simulator)
- As VDM-SL is being used, it uses VDMJ to parse the model [5]. This was a starting point for the tech stack, as VDMJ is also open source.
- VDMJ is written in Java [5], therefore to simplify implementing VDMJ into the Checklist Tester, it would be logical to use a Java virtual machine (JVM) language.

2.4.1 Formal Model

- There were a few ways of implementing the formal model into another application
- Some of these methods were provided by Overture [6]
 - RemoteControl interface
 - VDMTools API [7]
- However, both of these methods did not suit what was required as most of the documentation for RemoteControl was designed for the Overture Tool IDE. VDMTools may have handled the formal model differently
- The choice was to create a VDMJ wrapper, as the modules are available on Maven

2.4.2 Checklist Tester

JVM Language

- There are multiple languages that are made for or support JVMs [8]
- Requirements for language
 - Be able to interact with Java code because of VDMJ
 - Have Graphical User Interface (GUI) libraries
 - Have good support (the more popular, the more resources available)
- The main contenders were Java and Kotlin [9]
- Kotlin [9] was the choice in the end as Google has been putting Kotlin first instead of Java. Kotlin also requires less boilerplate code (e.g. getters and setters) [10]

Graphical User Interface

- As the tester is going to include a UI, the language choice was still important
- There are a variety of GUI libraries to consider using
 - JavaFX [11]
 - Swing [12]
 - Compose Multiplatform [13]
- The decision was to use Compose Multiplatform in the end, due to time limitations and having prior experience in using Flutter [14]
- Compose Multiplatform has the ability to create a desktop application and a server, which would allow for leeway if a server would be needed

2.4.3 Flight Simulator Plugin

- There are two main choices for flight simulators that can be used for professional simulation
 - X-Plane [15]
 - Prepar3D [16]
- X-Plane was the choice due to having better documentation for the SDK, and a variety of development libraries for the simulator itself
- For the plugin itself, there was already a solution developed by NASA, X-Plane Connect [17] that is more appropriate due to the time limitations and would be more likely to be reliable as it has been developed since 2015

Chapter 3

Design/Implementation

3.1 Components

Splitting up the project into multiple components has been useful for

- Aiding in planning to make the implementation more efficient
- Delegating specific work tasks
- Making the project modular, for example, allowing for a different simulator to be implemented with minimal need to refactor other parts of the codebase

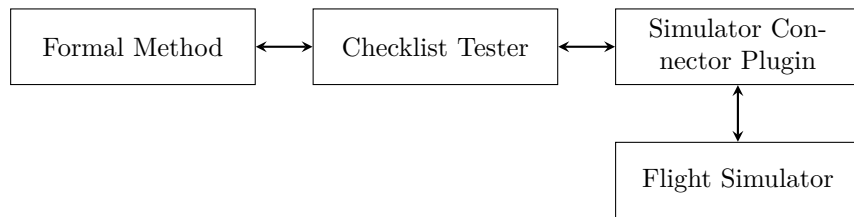


Figure 3.1: Abstract layout of components

Each of the components in Figure 3.1 will be covered in detail in this chapter.

3.2 Model

- Formal modelling is the heart of the logic for testing checklists
- Formal model created using VDM-SL
- It allows to test that the checklists have been completed in a proper manner - and that it is provable
- Model keeps track of
 - Aircraft state
 - Checklist state
- If an error were to occur in the model, this can be relayed that there was something wrong with running the test for the checklist, such as:
 - Procedure compromises integrity of aircraft
 - There is not enough time to complete the procedure
 - There is a contradiction with the steps of the checklist

3.3 Scenarios

- Use a Quick Reference Handbook (QRH) to find potential list of checklists to test
- Look at previous accident reports that had an incident related to checklists and test it with my tool to see if it will pick it up
- These previous accident reports can be good metrics to know what statistics to look out for

3.4 Decisions

Chapter 4

Results

4.1 Problems Found

4.2 LOC?

4.3 Reflection

4.4 Time Spent

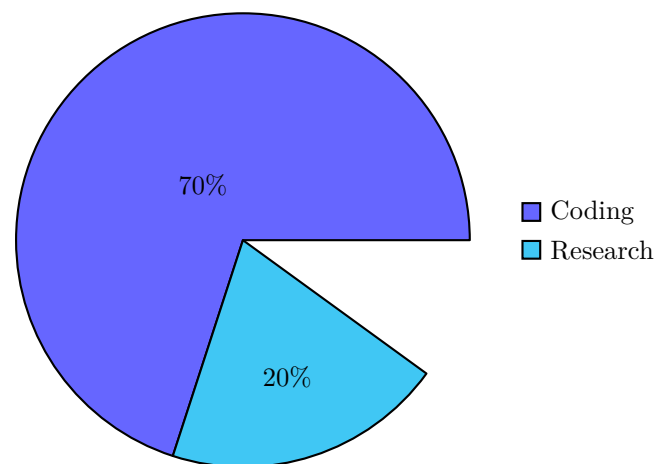


Figure 4.1: Time spent on sections of project

Chapter 5

Conclusion

5.1 Changes

5.2 Objectives

5.3 What Next

Appendix A

Formal Model

```
1 module Checklist
2 exports all
3 definitions
4
5 values
6   -- Before Start Checklist
7   -- Items in Aircraft
8   -- Flight Deck... (can't check)
9   fuel: ItemObject = mk_ItemObject(<SWITCH>, mk_Switch(<OFF>, false)→
10    );
11   pax_sign: ItemObject = mk_ItemObject(<SWITCH>, mk_Switch(<OFF>, →
12    true));
13   windows: ItemObject = mk_ItemObject(<SWITCH>, mk_Switch(<ON>, →
14    false));
15   -- Preflight steps
16   acol: ItemObject = mk_ItemObject(<SWITCH>, mk_Switch(<OFF>, false)→
17    );
18
19   aircraft_panels: Items = {"Fuel_Pump" |-> fuel, "Passenger_Signs" →
20    |-> pax_sign, "Windows" |-> windows, "Anti_Collision_Lights" →
21    |-> acol};
22
23   -- Checklist
24   -- Flight Deck... (can't check)
25   fuel_chkl: ChecklistItem = mk_ChecklistItem("Fuel_Pump", <SWITCH>,→
26    <ON>, false);
27   pax_sign_chkl: ChecklistItem = mk_ChecklistItem("Passenger_Signs",→
28    <SWITCH>, <ON>, false);
29   windows_chkl: ChecklistItem = mk_ChecklistItem("Windows", <SWITCH→
30    >, <ON>, false);
31   -- Preflight steps
32   acol_chkl: ChecklistItem = mk_ChecklistItem("Anti_Collision_Lights→
33    ", <SWITCH>, <ON>, false);
34
35   before_start_procedure: Procedure = [fuel_chkl, pax_sign_chkl, →
36    windows_chkl, acol_chkl];
37
38   aircraft = mk_Aircraft(aircraft_panels, before_start_procedure);
39
40 types
41   --@doc The dataref name in X-Plane
42   Dataref = seq1 of char;
43
44   -- Aircraft
```

```

33
34 -- Switches
35 --@doc The state a switch can be in
36 SwitchState = <OFF> | <MIDDLE> | <ON>;
37
38 --@LF why have a type kist as a rename?
39 ItemState = SwitchState; --@TODO | Button | ...
40
41 --@doc A switch, with the possible states it can be in, and the →
    state that it is in
42 Switch ::
43     position : SwitchState
44     middlePosition : bool
45     inv s ==
46         (s.position = <MIDDLE> => s.middlePosition);
47
48 -- Knob
49 Knob ::
50     position : nat
51     --@LF how can a state be an int? perhaps a proper type (i.e. →
        subset of int range or a union?)
52     states : set1 of nat
53     inv k ==
54         k.position in set k.states;
55
56 Lever = nat
57     inv t == t <= 100;
58
59 Throttle ::
60     thrust: Lever
61     reverser: Lever
62     inv t ==
63         (t.reverser > 0 <=> t.thrust = 0);
64
65 --@doc The type that the action of the button is
66 ItemType = <SWITCH> | <KNOB> | <BUTTON> | <THROTTLE>;
67
68 --@doc The unique switch/knob/etc of that aircraft
69 ObjectType = Switch | Knob | Throttle;
70 ItemObject ::
71     type : ItemType
72     object : ObjectType
73     inv mk_ItemObject(type, object) ==
74         cases type:
75             <SWITCH> -> is_Switch(object),
76             <KNOB>   -> is_Knob(object),
77             <THROTTLE>-> is_Throttle(object),
78             --<BUTTON> -> true
79             others -> true
80         end;
81
82 --@doc Contains each ItemObject in the Aircraft, e.g. Fuel Pump →
    switch
83 Items = map Dataref to ItemObject;
84
85 --@doc Contains the panels (all the items in the aircraft) and the →
    procedure
86 Aircraft ::

```

```

87     items : Items
88     procedure : Procedure
89     inv mk_Aircraft(i, p) ==
90     ({ x.procedure | x in seq p } subset dom i);
91
92 -- Checklist
93
94 --@doc Item of a checklist, e.g. Landing gear down
95 ChecklistItem ::
96     --@LF again, empty string here doesn't make sense.
97     procedure : Dataref
98     type : ItemType
99     --TODO Check is not only SwitchState
100    check : SwitchState
101    checked : bool;
102
103 --@doc This is an item in the aircraft that complements the item →
    in the procedure
104 ItemAndChecklistItem ::
105     item : ItemObject
106     checklistItem: ChecklistItem
107     inv i == i.item.type = i.checklistItem.type;
108
109 --@doc A section of a checklist, e.g. Landing Checklist
110 --@LF shouldn't this be non-empty? What's the point to map a →
    checklist name to an empty procedure? Yes.
111 Procedure = seq1 of ChecklistItem
112     inv p ==
113         --@LF the "trick" for "false not in set S" is neat. It →
            forces a full evaluation, rather than short circuited →
            (i.e. stops at first false).
114         -- I presume this was intended.
115         false not in set {
116             let first = p(x-1).checked, second = p(x).checked in
117                 --@LF boolean values don't need equality check
118                 second => first--((first = true) and (second = →
                    false))
119             | x in set {2,...,len p}};
120
121 functions
122 -- PROCEDURES
123 --@doc Finds the index of the next item in the procedure that →
    needs to be completed
124 procedure_next_item_index: Procedure -> nat1
125 procedure_next_item_index(p) ==
126     hd [ x | x in set {1,...,len p} & not p(x).checked ]--p(x).→
        checked = false]
127 pre
128     -- Checks procedure has not already been completed
129     not procedure_completed(p)--procedure_completed(p) = false
130 post
131     -- Checks that the index of the item is the next one to be →
        completed
132     --@LF your def is quite confusing (to me)
133     --@LF how do you know that RESULT in inds p? Well, the →
        definition above okay.
134     -- but you can't know whether p(RESULT-1) will! What if →
        RESULT=1? p(RESULT-1)=p(0) which is invalid!

```

```

135      (not p(RESULT).checked)
136      and
137      (RESULT > 1 => p(RESULT-1).checked)
138      --p(RESULT).checked = false
139      --and if RESULT > 1 then
140      --    p(RESULT-1).checked = true
141      --else
142      --    true
143      ;
144
145      -- --@doc Checks if all the procedures have been completed
146      -- check_all_proc_completed: Checklist -> bool
147      -- check_all_proc_completed(c) ==
148      --    false not in set { procedure_completed(c(x)) | x in set →
149      --      {1,...,len c} };
150
151      -- --@doc Gives the index for the next procedure to complete
152      -- next_procedure: Checklist -> nat1
153      -- next_procedure(c) ==
154      --    hd [ x | x in set {1,...,len c} & not procedure_completed(c→
155      --      (x))]
156      -- post
157      --    RESULT <= len c;
158
159      --@doc Checks if the procedure has been completed
160      procedure_completed: Procedure -> bool
161      procedure_completed(p) ==
162      false not in set { p(x).checked | x in set {1,...,len p} };
163
164      --@doc Checks if the next item in the procedure has been completed
165      check_proc_item_complete: Procedure * Aircraft -> bool
166      check_proc_item_complete(p, a) ==
167      --@LF here you have a nice lemma to prove: →
168      --    procedure_next_item_index(p) in set inds p!
169      --    I think that's always true
170      let procItem = p(procedure_next_item_index(p)),
171      --@LF here you can't tell whether this will be true? i→
172      --    .e. procItem.procedure in set dom a.items?
173      item = a.items(procItem.procedure) in
174
175      --TODO need to be able to check for different types of →
176      --    Items
177      procItem.check = item.object.position
178
179      pre
180      procedure_completed(p) = false
181      --@LF perhaps add
182      --and
183      --p(procedure_next_item_index(p)).procedure in set dom a.items→
184      --    ?
185      ;
186
187      --@doc Marks next item in procedure as complete
188      mark_proc_item_complete: Procedure -> Procedure
189      mark_proc_item_complete(p) ==
190      let i = procedure_next_item_index(p), item = p(i) in
191      p ++ {i |-> complete_item(item)}
192      pre
193      procedure_completed(p) = false;

```

```
187
188 --@doc Completes an item in the procedure
189 do_proc_item: ItemObject * ChecklistItem -> ItemAndChecklistItem
190 do_proc_item(i, p) ==
191     let objective = p.check,
192     checkckItem = complete_item(p) in
193     -- Checks if the item is in the objective desired by the →
194     checklist
195     if check_item_in_position(i, objective) then
196         mk_ItemAndChecklistItem(i, checkckItem)
197     else
198         mk_ItemAndChecklistItem(move_item(i, p.check), →
199                                 checkckItem)
200 pre
201     p.checked = false
202 post
203     -- Checks the item has been moved correctly
204     check_item_in_position(RESULT.item, p.check);
205
206 --@doc Completes a procedure step by step
207 -- a = Aircraft
208 complete_procedure: Aircraft -> Aircraft
209 complete_procedure(a) ==
210     let procedure = a.procedure in
211     mk_Aircraft(
212         a.items ++ { x.procedure |-> do_proc_item(a.items(x.→
213             procedure), x).item | x in seq procedure },
214         [ complete_item(x) | x in seq procedure ]
215     )
216 pre
217     not procedure_completed(a.procedure)
218 post
219     procedure_completed(RESULT.procedure);
220
221 -- AIRCRAFT ITEMS
222 --@doc Marks ChecklistItem as complete
223 complete_item: ChecklistItem -> ChecklistItem
224 complete_item(i) ==
225     mk_ChecklistItem(i.procedure, i.type, i.check, true)
226 pre
227     i.checked = false;
228
229 --@doc Moves any type of Item
230 move_item: ItemObject * ItemState -> ItemObject
231 move_item(i, s) ==
232     -- if is_Switch(i) then (implement later)
233     let switch: Switch = i.object in
234     if check_switch_onoff(switch) and (s <> <MIDDLE>) and →
235     switch.middlePosition then
236         mk_ItemObject(i.type, move_switch(move_switch(→
237             switch, <MIDDLE>), s))
238     else
239         mk_ItemObject(i.type, move_switch(switch, s))
240 pre
241     wf_item_itemstate(i, s)
242     and not check_item_in_position(i, s);
243     -- and wf_switch_move(i.object, s);
244
```



```

240  --@doc Moves a specific switch in the aircraft
241  move_switch: Switch * SwitchState -> Switch
242  move_switch(i, s) ==
243      mk_Switch(s, i.middlePosition)
244  pre
245      wf_switch_move(i, s)
246  post
247      RESULT.position = s;
248
249  --@doc Checks if the switch is in the on or off position
250  check_switch_onoff: Switch -> bool
251  check_switch_onoff(s) ==
252      let position = s.position in
253          position = <OFF> or position = <ON>
254  post
255      -- Only one can be true at a time
256      -- If the switch is in the middle position, then RESULT cannot be true
257      -- If the switch is in the on/off position, then the RESULT will be true
258      (s.position = <MIDDLE>) <> RESULT;
259
260  --@doc Checks if the item is already in position for the desired state for that item
261  check_item_in_position: ItemObject * ItemState -> bool
262  check_item_in_position(i, s) ==
263      -- if is_Switch(i) then (implement later)
264      i.object.position = s
265  pre
266      wf_item_itemstate(i,s);
267
268  --@doc Checks if the Item.object is the same type for the ItemState
269  wf_item_itemstate: ItemObject * ItemState -> bool
270  wf_item_itemstate(i, s) ==
271      (is_Switch(i.object) and is_SwitchState(s) and i.type = <SWITCH>)
272      --TODO check that the item has not already been completed before moving item
273      --TODO add other types of Items
274      ;
275
276  --@doc Checks if the move of the Switch is a valid
277  wf_switch_move: Switch * SwitchState -> bool
278  wf_switch_move(i, s) ==
279      -- Checks that the switch not already in the desired state
280      i.position <> s and
281      -- The switch has to move one at a time
282      -- Reasoning for this is that some switches cannot be moved in one quick move
283      if i.middlePosition = true then
284          -- Checks moving the switch away from the middle position
285          (i.position = <MIDDLE> and s <> <MIDDLE>)
286          -- Checks moving the switch to the middle position
287          <> (check_switch_onoff(i) = true and s = <MIDDLE>)
288      else
289          check_switch_onoff(i) and s <> <MIDDLE>;
290

```

```
291
292 end Checklist
293
294 /*
295 //@LF always a good idea to run "qc" on your model. Here is its output+
    . PO 21 and 22 show a problem.
296 //@LF silly me, this was my encoding with the cases missing one +
    pattern :-). I can see yours has no issues. Good.
297
298 > qc
299 PO #1, PROVABLE by finite types in 0.002s
300 PO #2, PROVABLE by finite types in 0.0s
301 PO #3, PROVABLE by finite types in 0.0s
302 PO #4, PROVABLE by finite types in 0.0s
303 PO #5, PROVABLE by finite types in 0.0s
304 PO #6, PROVABLE by finite types in 0.0s
305 PO #7, PROVABLE by finite types in 0.0s
306 PO #8, PROVABLE by finite types in 0.0s
307 PO #9, PROVABLE by finite types in 0.001s
308 PO #10, PROVABLE by finite types in 0.001s
309 PO #11, PROVABLE by direct (body is total) in 0.003s
310 PO #12, PROVABLE by witness s = mk_Switch(<MIDDLE>, true) in 0.001s
311 PO #13, PROVABLE by direct (body is total) in 0.001s
312 PO #14, PROVABLE by witness k = mk_Knob(1, [-2]) in 0.0s
313 PO #15, PROVABLE by direct (body is total) in 0.0s
314 PO #16, PROVABLE by witness t = 0 in 0.0s
315 PO #17, PROVABLE by direct (body is total) in 0.001s
316 PO #18, PROVABLE by witness t = mk_Throttle(0, 0) in 0.001s
317 PO #19, PROVABLE by direct (body is total) in 0.002s
318 PO #20, PROVABLE by witness i = mk_ItemObject(<KNOB>, mk_Knob(1, [-1]))+
    ) in 0.002s
319 PO #21, FAILED in 0.002s: Counterexample: type = <BUTTON>, object = +
    mk_Knob(1, [-1])
320 Causes Error 4004: No cases apply for <BUTTON> in 'Checklist' (formal/+
    checklist.vdmsl) at line 119:13
321 ----
322 ItemObject':_total_function_obligation_in_'Checklist'_(formal/+
    checklist.vdmsl)_at_line_118:13
323 (forall_mk_ItemObject'(type, object):ItemObject'!_&
324 _is_(inv_ItemObject'(mk_ItemObject'!(type,_object)),_bool))
325
326 PO_#22,_FAILED_by_direct_in_0.005s:_Counterexample:_type=_<BUTTON>
327 PO_#23,_PROVABLE_by_witness_type=_<KNOB>,_object=_mk_Knob(1,_[-1])_+
    in_0.002s
328 PO_#24,_PROVABLE_by_direct_(body_is_total)_in_0.001s
329 PO_#25,_PROVABLE_by_witness_i=_mk_ItemAndChecklistItem(mk_ItemObject+
    (<KNOB>,_mk_Knob(1,_[-1])),_mk_ChecklistItem([],_<KNOB>,_<MIDDLE>,+
    _true))_in_0.001s
330 PO_#26,_MAYBE_in_0.003s
331 PO_#27,_MAYBE_in_0.003s
332 PO_#28,_MAYBE_in_0.002s
333 PO_#29,_PROVABLE_by_witness_p=_[mk_ChecklistItem([],_<BUTTON>,_<+
    MIDDLE>,_true)]_in_0.001s
334 PO_#30,_MAYBE_in_0.002s
335 PO_#31,_MAYBE_in_0.001s
336 PO_#32,_MAYBE_in_0.003s
337 PO_#33,_MAYBE_in_0.002s
338 PO_#34,_MAYBE_in_0.001s
```

```

339 PO_#35, MAYBE_in 0.002s
340 PO_#36, MAYBE_in 0.009s
341 PO_#37, MAYBE_in 0.008s
342 PO_#38, MAYBE_in 0.007s
343 PO_#39, MAYBE_in 0.009s
344 PO_#40, MAYBE_in 0.002s
345 PO_#41, MAYBE_in 0.001s
346 PO_#42, MAYBE_in 0.001s
347 PO_#43, MAYBE_in 0.002s
348 PO_#44, MAYBE_in 0.002s
349 PO_#45, MAYBE_in 0.003s
350 PO_#46, MAYBE_in 0.002s
351 PO_#47, MAYBE_in 0.002s
352 PO_#48, MAYBE_in 0.001s
353 PO_#49, MAYBE_in 0.001s
354 PO_#50, MAYBE_in 0.0s
355 PO_#51, MAYBE_in 0.0s
356 PO_#52, MAYBE_in 0.005s
357 PO_#53, PROVABLE_by_trivial_p_in_set(dom_checklist)_in 0.001s
358 PO_#54, MAYBE_in 0.006s
359 PO_#55, MAYBE_in 0.0s
360 PO_#56, MAYBE_in 0.001s
361 PO_#57, MAYBE_in 0.001s
362 PO_#58, MAYBE_in 0.001s
363 PO_#59, MAYBE_in 0.001s
364 PO_#60, MAYBE_in 0.001s
365 PO_#61, MAYBE_in 0.001s
366 PO_#62, MAYBE_in 0.0s
367 PO_#63, PROVABLE_by_finite_types_in 0.001s
368 PO_#64, PROVABLE_by_finite_types_in 0.001s
369 PO_#65, PROVABLE_by_finite_types_in 0.001s
370 PO_#66, MAYBE_in 0.001s
371 >
372 */

```

References

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