A Methodology for integration of formal methods in a healthcare case study

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Abstract

When developing safety-critical systems, it is necessary to satisfy not only functional requirements defining the set of tasks to be performed by the system, but also safety requirements describing the characteristics the system should possess in order to ensure proper safety. Reliability is, as well, an acute issue in the development of safety-critical systems. Enhancement of safety and reliability can be achieved by applying formal methods, while complexity of large systems can be mastered using a graphical language for modelling, e.g., UML. Here we introduce a UML-based development process that incorporates safety analysis and provides a logical interface to a formal refinement based development in B-action systems. The tools associated with the B Method provide a good mechanised support for proving the correctness of the development within B-action systems. We show the feasibility of our development process within a healthcare case study where we develop a safety-critical drug discovery system.

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TUCS Research Group

Programming Methodology Group

1. Motivation for using formal methods

While developing safety-critical systems, it is necessary to satisfy not only functional requirements defining the set of tasks to be performed by the system, but also safety requirements describing which characteristics the system should possess in order to ensure proper safety. Safety and reliability are acute issues for these systems under construction [Storey96, Troubitsyna00]. Reliability means the correct functioning of the system under a given set of operating conditions. It constitutes one of the most important properties that, for example, the drug discovery systems and the biomedical research should provide. Reliability should guarantee an extremely high precision and the constant level of quality of experiments to be performed. The need to achieve these requirements introduces specificity in the typical process of development of a control system.

Safety is the property of a system which ensures that it will not harm humans, environment or equipment. According to the classifications normally used in safety-critical systems the severity of the direct harm to the humans using a drug discovery systems is quite moderate. However, the indirect harm caused by the results of incorrectly performed experiments might be catastrophic. The results of failures of such a system might also lead to significant economical losses. Hence, the system is both safety and money critical.

Enhancement of both safety and reliability can be achieved by applying formal methods. In the past few years regulatory requirements for drug discovery systems have tightened. Because of these there is a need to introduce formal methods in the development lifecycle to prepare for the future regulations. Also the competition in the field constantly requires shortening the marketing window. Since the application of formal methods allows early error discovery, formal methods could speed up the development process.

A software development method that is industry-driven and in fact has become the 'de facto' software-modeling standard is UML (the Unified Modeling Language). UML is a graphical language for specifying, visualizing, developing and documenting software-intensive systems [UML1.4]. It encompasses good engineering practices that have proven successful in the modeling of large and complex systems.

Complex distributed systems are favourably developed by stepwise adding details to the system. The B-action systems is a formalism for supporting this kind of development of distributed systems [BW96,WS98]. The formalism uses stepwise refinement for developing a system correct by construction. Each refinement step is accompanied by proofs. The B Method [Abrial96] and its associated tool provide us with a good mechanised support for refinement based development. The B Method has already been successfully used in industrial projects.

2. Formal development of the healthcare case study

In this report we study the integration of formal methods applied on a health care case study. We introduce a UML-based development process that incorporates safety analysis and interfaces with a formal development in B.

2.1 Presentation of the Wallac case study

PerkinElmer Life Sciences designs, manufactures, develops, and markets analytical systems for use in drug discovery, mass population screening, and other bioresearch and clinical diagnostics areas. PerkinElmer Life Sciences was formed from the international Wallac Group, and is today a worldwide organization with about one thousand employees.

PerkinElmer Life Sciences (later in the document referred to as Wallac) supplies complete analytical systems. The systems are used to provide researchers and clinicians with reliable determinations of 'difficult to measure' substances found in blood or other biological sample materials. Typically, the substance to be measured is tagged with a radionuclide or a fluorescent or luminescent label. The amount of the substance is then determined from the 'signal', or the amount of radiation or light given off by the label. The manufactured analytical systems include reagents, sample handling and measuring instrumentation, as well as computer software.

The team of the Computer Science Department at Aabo Akademi University (later in the document referred to as Aabo Akademi) is conducting a parallel development of a new product of Wallac's – Fillwell™, a workstation preparing samples [PerkinElmer01]. The workstation is shown in Fig. 1. The system belongs to the class of products for drug discovery and bioresearch. The Fillwell microplate liquid handling workstation offers significantly advanced features in the line of the sample preparation systems. The Fillwell base unit consists of a dispense head dispensing liquid into microplates on a processing table. A gantry moves the dispense head with high precision and speed from one plate to another.

Fig. 1: The Fillwell microplate liquid handling workstation.

The Fillwell workstation is the first liquid handling system specifically designed for high density microplates. The system is modular and can therefore be customized into a variety of configurations. The dispense head can have up to 384 tips attached. With the tips the head can perform automated pipetting into plates with 96, 384 or 1536 wells. The head provides a precise dispensing with volumes from 0.5 to 300 µl. The processing table contains up to 6 plate positions. An extension with three plate positions is easily removable. In Fig. 1 this processing table extension has been removed. In order for the dispensing head to be able to reach all the positions on the processing table it is mounted on a gantry that can move in XYZ-directions. The precision of the gantry is very high with an accuracy of 100 µm. The system can function as a standalone workstation or be integrated into a robot.

The main application of the Fillwell workstation is drug discovery. Within this application area the system can be used for microplate replication, for dilution, transfer and addition of the liquid in the plates, for reformatting of plates with different densities (number of wells), as well as for rapid plate filling to homogenous and cell based systems. The FillWell system is a safety-critical system. Safety is the property of a system, which ensures that it will not harm humans, environment or equipment. The direct harm to the humans using the drug discovery systems is quite moderate according to the classification for normal safety-critical systems. However, the indirect harm caused by the results of incorrectly performed experiments might be catastrophic. Furthermore, the system can be used to handle extremely expensive substances (valued up to a billion EURO per kg) as well as serve as a part of an expensive production chain. Hence, failures of such a system might result in significant economical losses and the system can also be considered as money critical.

2.2 The setting of the case study

The case study is organised using an industry-as-laboratory approach. This means that the researchers in academia provide the formal methods and B expertise while the experts at the R&D department of the industrial partner bring the domain knowledge to the team.

In order to come up with a good methodology for the development we started with a smaller part of the case study concentrating on modelling the dispense head and its movement up and down as well as its dispensing of liquid. However, the branch of development of medical and pharmaceutical equipment is highly competitive. Because of that, the requirement to preserve confidentiality of the equipment under construction was very strict. As the product has been confidential until recently (mid September) we have developed a mirror case study, called the Robot analyser, in order to have a public case study as an example of the methodology. We have chosen a mirror case study that models the significant and critical aspects of the Fillwell case study concerning the precision of movement and liquid handling. Both the case studies belongs to the same class of systems.

In the Fillwell case study we have a workstation dispensing to and aspirating from plates. Our mirror case study is a robot analyser that analyses samples on a plate that is placed on a movable operating table. The movement of the operating table corresponds to the movement of the dispense head, while the analysing corresponds to the dispensing. A first extension of the systems would be to take into consideration the XY-movement of the dispense head and, hence, the corresponding rotation of the robot to be able to work with more than one plate.

2.3 The requirements of the case study

The Robot analyser consists of two interacting parts, a Robot and an Analyser. We concentrate here on the Analyser. The task of the Robot is to place a plate to be analysed into the Analyser, as well as to remove an analysed plate from it.

The Analyser has an operating table – a horizontal surface on which a plate is placed by the Robot. The Analyser can move its operating table to pick up a plate from the Robot, move the table to its analysing component, analyse the plate, as well as move the table to a position from which the Robot can remove the plate. During the analysis it is checked that there is enough liquid on the plate before the analysis and that the right amount of liquid was used during the analysis. The quality of the analysis should be kept at a constantly high level.

The Robot has two arms, one for placing a plate in the Analyser and the other for removing this plate. These arms are at different heights. Therefore, the table has to be at different positions for placing and removing plates:

Upper end position:	A plate is analysed by the analysing component
Middle position:	Arm 1 of the Robot places a plate into the Analyser
Lower end position:	Arm 2 of the Robot removes a plate from the Analyser

Initially the Analyser is at its middle position and it is empty.

Due to the fact that the operating table and the Robot arms may collide we define the following *safety requirements*:

- When the Robot is ready to load the Analyser, arm 1 may extend only if the table is in its middle position.
- When the Robot is ready to unload the Analyser, arm 2 may extend only if the operating table is in its lowest position.
- The table may move only when the respective Robot arm has retracted.
- The table must not move beyond its upper and lower end position.

During a *typical course of events* the following sequence of actions happens with a plate. Here, we have not considered the possible failures.

1) The Analyser moves the operating table to the middle position (*move(zmid)*).
2) The Analyser waits to receive a plate from the first Robot arm after the Robot has picked up a plate and rotated to the Analyser (*receive*).
3) The Analyser moves the operating table to the upper end position (*move(zmax)*).
4) The Analyser analyses the plate (*analyse*).
5) The Analyser moves the operating table to the lower end position (*move(zmin)*).
6) The Analyser waits to deliver an analysed plate to the second Robot arm and the Robot rotates to pass the plate on to another device (*deliver*).

We can note that other courses of events are possible depending on in which order the commands *move, receive, analyse* and *deliver* are given. In order to prohibit the Analyser to analyse a plate and move an infinite number of times, only a certain number of moves are allowed to be performed in a row before some other action need to be taken by the Analyser. Similarly, only a certain number of analyses on one plate are allowed before the plate has to be delivered.

2.4 The integrated development process proposed for the case study

The core idea of our overall development process is based on applying both safety analysis and B reasoning about correctness to an already constructed UML specification of the eventual control system. Usually such a specification is neither obvious, nor simple to obtain for a large and complex final system, given only the initial informal requirements. Hence, a more scalable approach is required for producing at least the first specification of the system. The initial specification should already ensure safety and be proved to be consistent. We elaborate on the initial specification by introducing functionality details in a stepwise manner. The correctness of the refinement of the initial specification into a specification incorporating these details is proved using the B-action systems. In each refinement step, safety properties of the system are preserved. The entire development process also requires a consistent documentation strategy that enables smoother evolution and reuse of the produced system. UML provides us with such documentation means at every stage of the development process. When developing control systems the final detailed system is decomposed into a plant, a controller, sensors and actuators [PRTWJ01].

Hence, our development process comprises two main phases. First, a system specification is developed from the initial informal requirements. Second, upon proving its consistency with these requirements, the specification is stepwise refined into a concrete, more detailed system using the B-action systems. Safety and reliability considerations are incorporated into the entire process.

3 Safety aspects of the development

The development process should ensure safety and reliability of the system under construction. Therefore, we need to incorporate safety analysis in the existing development process. Only if safety and reliability attributes are considered from the early stages of the system development, the required dependability of the system can be achieved.

3.1 Hazard Analysis

The safety requirements result from safety analysis, which includes hazard analysis, assignment of dependability attributes and assessment of system criticality [Leveson95, Storey96]. Handling of hazards plays a paramount role in safety analysis. A *hazard* is a state of the system that, together with other conditions in the environment of the system, leads inevitably to an accident [Leveson95]. *Hazard analysis* allows the designers to identify the potential danger associated with a system. It includes hazard identification, classification and decision on methods required to handle the hazards. The identified hazards are distinguished by *risks* associated with them. The concept of risk combines the severity and frequency of a hazard [Storey96]. The severity of a hazard is a measure of the consequences of an accident caused by this hazard. The identification of the hazards associated with a system and their classification provide information for finding the appropriate methods for dealing with the hazards. Hazard analysis supplies also more information regarding routine system behaviour, behaviour in presence of failures, failure modes of system components.

This information provides a basis for the assignment of the appropriate dependability attributes as well as the level of criticality (dependability) to the system under construction. The higher the level of system criticality, the more rigorous the design methods.

3.2 Safety analysis within software development

Nowadays, software is used in the vast majority of safety-critical systems. Therefore, the design of *embedded software* plays an important role in development of dependable systems. Obviously, the software used in safety-critical applications cannot of itself produce any direct harm to the controlled environment. It is the equipment being incorrectly controlled by software, which causes harm directly. We argue that program refinement constitutes a suitable approach to the development of correct software for safety-critical applications.

While designing software for safety-critical systems, it is necessary to consider the possible safety implications, i.e., to ensure that the suggested design does not introduce additional hazards. Moreover, we should ensure that controlling software reacts promptly on hazardous situations by trying to force the system back to a safe state. Clearly, this goal can be achieved only if the information provided by safety analysis is taken into account in the process of software development.

We propose an approach for conducting software development hand-in-hand with safety analysis as presented in Fig 2. We observe that both the safety analysis and the stepwise program development conduct reasoning from an abstract level to a concrete level. Safety analysis starts by identifying hazards that are potentially dangerous, and proceeds by producing detailed descriptions of them together with finding the means to cope with these hazards. We as other researchers [Leveson96] argue that only if safety and reliability attributes are considered from the early stages of the system development, the required dependability of the system can be achieved.

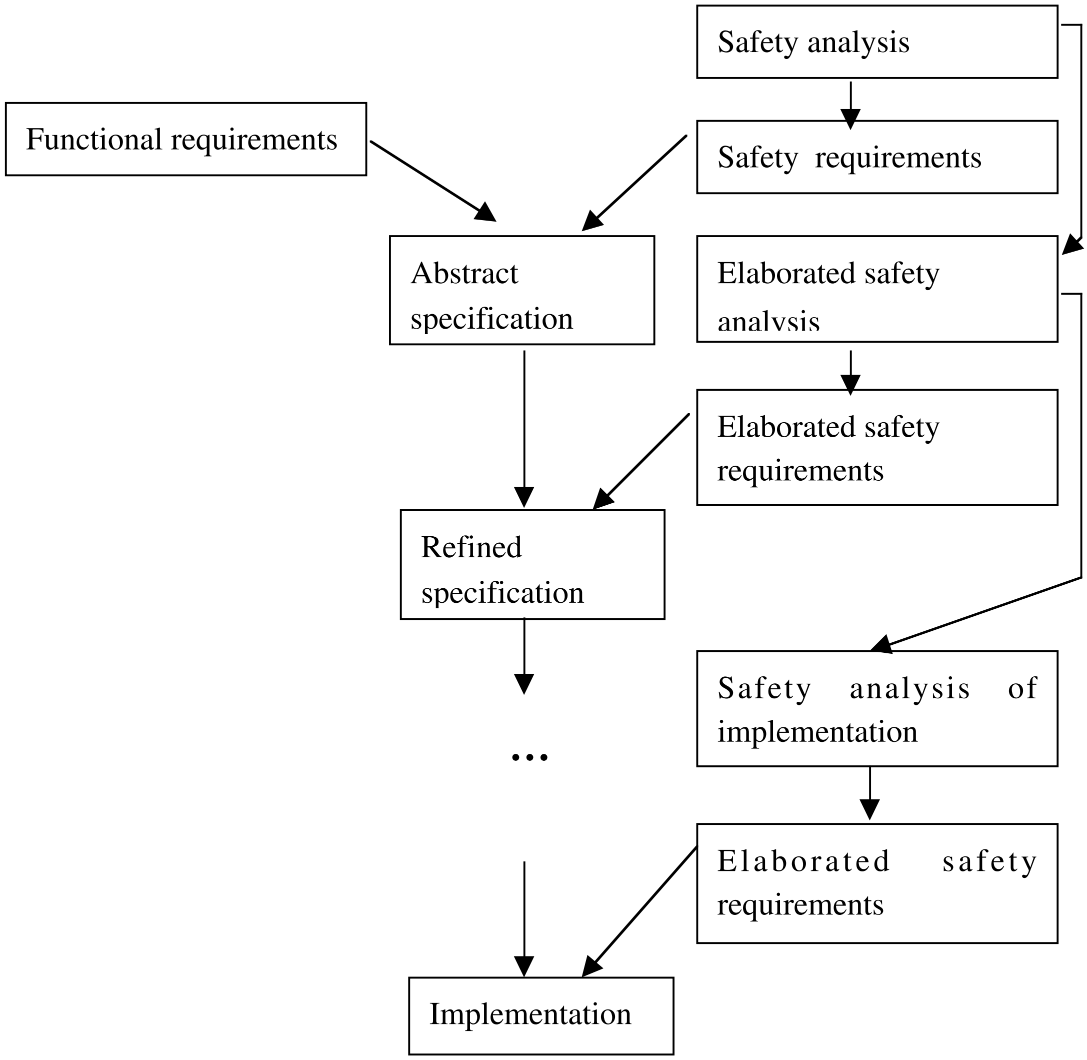

Fig. 2: Safety analysis and stepwise system development

The refinement process starts by producing an abstract specification describing what should be done rather than how it should be done. Each refinement step allows us to incorporate more implementation details in the abstract specification, so that we end up in a program. Therefore, we can incorporate the information that becomes available at each stage of the safety process by performing corresponding refinements of the initial specification. Hence, in the Analyser development the safety analysis will be woven into the UML- and B-action systems development as will be seen in the following sections.

3.3 Dependability impairment

A safety-critical system is usually a control system with a computer-based controller managing a plant. There are two main entities involved: an environment and a controller. While developing a specification for a control system, we model the behaviour of the overall system, that is, the physical environment and the controller together. In report [PRTWJ01] we elaborate more on control systems. This allows us to state explicitly the assumptions that we make about how the environment behaves. By specifying the overall system we can abstract away from means of interaction between the controller and the plant (via sensors and actuators) and, as a result, obtain more succinct initial specification. At the later stages of the development process, when the desired level of detail is achieved, we separate the controller and the plant, thus, obtaining the specification of the controller as such.

The plant behaviour evolves according to the involved physical processes and the control signals provided by the controller. The controller observes the behaviour of the plant and adjusts it to guarantee intended plant functionality. While observing the plant behaviour the controller reacts on certain events requiring its intervention. Hence, that kind of system is a typical example of a reactive system.

3.4 Presence of failures

The controller bases its decision on the information that it obtains from sensors. Due to faults of the system components and imprecision of the sensors, the controller obtains an approximation of the equipment state rather than a real state. Failure occurrences deteriorate this approximation and potentially lead to dependability impairment by:

- loss of precision in the function execution, i.e., a decreased reliability of the system,
- system failure as a result of violation of safety,
- complication in synchronizing the involved machines (which has implications for both safety and reliability).

Therefore, handling failures constitutes an important aspect in developing safety-critical systems.

3.5 Handling failures

In order to build a controller able to withstand components failures the following actions are required:

- to understand the nature of faults and their impact on the overall system,
- to decide on the detection procedures, repair procedures, functioning of the system in presence of failures,
- to introduce an effective maintenance procedure.

To incorporate the results of safety analysis in a systematic way in the refinement process the following methodological aspects should be addressed:

- Modeling fault occurrence
- Modeling fault detection
- Modeling system behavior in presence of faults
- Modeling synchronization in presence of faults
- Modeling different operating modes and transition between modes including the system failure
- Design and specification of a maintenance procedure: analysis of additional safety percussions during maintenance, specification of system behavior in the manual mode
- Specification of the execution log

These actions of handling failures are taken in the UML- and B-action systems development described in the following sections.

4. UML-development incorporating safety aspects

The starting point of a system development is an informal specification describing the services desirable from the eventual product, with no or few hints about the various software and hardware parts. We consider this to be the most general starting point for the development process of a control system. The most important role is played by UML in the first phase of the process, when a system specification is determined from the initial requirements. We define a method for using the UML diagrams for designing a control system specification [PS00]. An essential contribution at this level is the embedding of the safety analysis within the UML method.

We depict the informal requirements of the healthcare case study with UML diagrams. The functional requirements of the system are captured together with their relationships in a use case diagram. The reliability and safety issues are given in the specification of the use cases as structured English text. Then the logically related use cases are determined, and grouped together into a control system component in component and class diagrams. The behaviour of the component is specified with a statechart diagram. The informal specification of the eventual system is thus gradually captured and made more and more precise throughout these diagrams.

4.1 Functional requirements capturing safety issues

The *functional requirements* of the system are depicted, together with their relationships in a use case diagram as presented in Fig. 3. Each use case expresses a service that the system will eventually provide to a user. In Fig. 3 we have a system with three use cases.

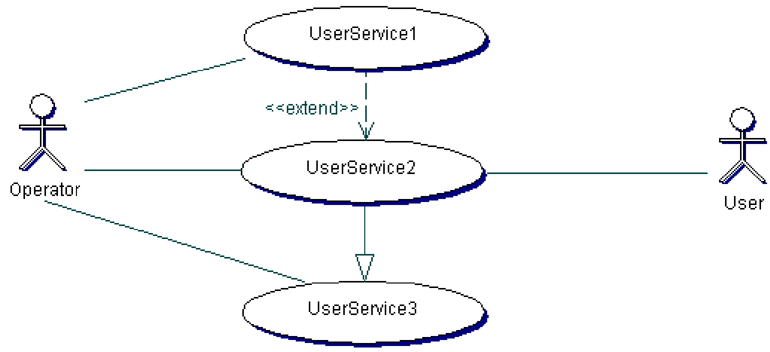

Fig. 3: A use case diagram

To exemplify the integrated methodology we create the controlling software for an analysing device, here called the Analyser. The Analyser is restricted to move vertically and to analyse blanks/plates. The simplified operations form the protocol of the analysing device. This protocol is described below. A typical protocol can be as follows:

1) Move to middle position
2) Receive plate
3) Move to upper end position
4) Analyse the plate
5) Move to lower end position
6) Deliver plate
7) Repeat from step 1.

Hence, the functional requirements of the Analyser is to analyse plates, to receive plates from and deliver plates to the Robot and to move the operating table to its three possible positions. A use case diagram of the Analyser is given in Fig. 4.

The Robot and the Analyser interact by the Robot loading a blank to the Analyser *receiving* it, as well as by the Robot unloading a blank from the Analyser *delivering* this blank. The Robot is the active partner while the Analyser is the passive partner during this interaction.

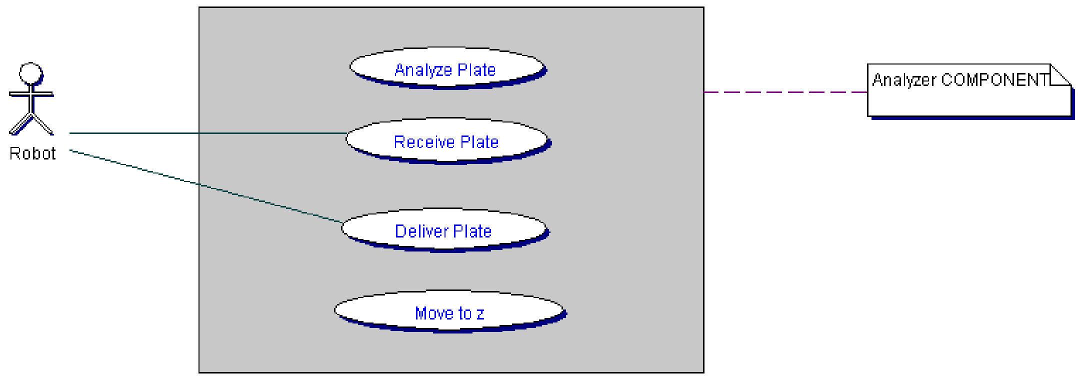

Fig. 4: Use Case Diagram for the Analyser.

Besides these functional services we also capture, at a reasonable level of detail, the *reliability and safety issues* related to the determined functional services. These issues are not captured in the diagram, but in the specification of the use cases, most commonly expressed as structured English text. Hence, at this level the vocabulary of the whole system is fixed, an overview statement is defined, and the goals, attributes and basic functions, as well as their possible deviations are all captured by careful systematic analysis. The Analyser in our example is seen as a small part of the whole system.

Goals

We consider the following goals for the operator and user (as in Fig. 3) of the whole system in our case study.

1) Easy operation of the whole assembly by humans.
2) Fast and accurate control of the mechanical parts.
3) Fast and accurate analysis of the protocol results.
4) Automatic inventory of the processing operations (perhaps stored in a log).
5) Careful functional and safety analysis for simulating the protocol of the Analyser operation.

The first four goals are common to the whole project and refer to the eventual software. The fifth goal refers essentially to the process of producing the eventual software. We apply a combination of formal methods (the B Method and B-action systems), UML and safety analysis for checking the quality of the eventual software and for producing this software, which we could then claim to be correct. This fifth goal is the most important to us.

Basic functions

The basic functions for the eventual software of the healthcare case study are as follows:

1) Capture the protocol information when entered.
2) Communicate the protocol information with the mechanical parts.
3) Record the running protocol.
4) Inform about failures and the failure points.

These are the functions we have identified for the controlling software of the system. In this case study we are only interested in functions 1, 2 and 4.

We assume that the position detection of the operating table is absolutely reliable in the Analyser. The *risks* and *dependencies* of the system are listed during the development process.

Use cases incorporating the possible failures

We have identified four use cases, *move*, *receive*, *analyse* as well as *deliver* for the Analyser as shown in Fig. 4. We consider these use cases as subroutines, since it is more convenient with subroutines for the purpose of safety and reliability analyses.

Subroutine Move captures the moving of the operating table to the position *pos*.

<u>Typical course of events</u>:

1. Analyser receives command *move to position pos* from protocol.
2. System checks if pos is a valid position; if not, then MF1.
3. System checks if it is safe to move; if not then MF2.
4. System checks if current_pos /= pos and if further moves are allowed; if not then MF3.
5. Analyser moves to position pos.
6. System checks if current_pos = pos; if not then MF4.
7. Signal move_ok.

<u>Failure reports</u>:

MF1. Input parameter pos is outside the valid range.
Remedy: User changes parameter pos, identifies the cause and resumes or aborts calling protocol execution.

MF2. Robot is not safe.
Remedy: Wait a while for the Robot to become safe.

MF3. Erroneous move command. Protocol failure.
Remedy: Check and change protocol or abort.

MF4. Analyser has not reached position pos.
Remedy: Calibrate and resume or abort calling protocol execution

Subroutine Receive captures the analysing of a plate from the Robot, provided the operating table is at its middle position and there is no plate in the Analyser.

Typical course of events:

1. Analyser receives command *receive* from protocol.
2. System checks if Robot has a plate available; if not then RF1.
3. System checks if current_pos = middle position to Receive; if not RF2.
4. System checks if the Analyser is empty; if not then RF3.
5. Robot loads the Analyser.
6. System checks if plate has been received; if not then RF4.
7. Signal receive_ok.

Failure reports:

RF1. Robot is not ready to load the Analyser.
Remedy: Wait a while for the robot to become ready.

RF2. Current_pos /= middle position to Receive.
Remedy: User identifies the cause and moves the Analyser manually.

RF3. Plate is present.
Remedy: User identifies the cause, and unloads the Analyser manually or aborts.

RF4. The Analyser has not been loaded.
Remedy: User identifies the cause, loads the Analyser manually and resumes or aborts.

Subroutine Analyse captures the receiving of a plate from the Robot, provided the operating table is at its upper end position and there is a plate in the Analyser.

Typical course of events:

1. Analyser receives command *analyse* from protocol.
2. System checks if a plate is present in the Analyser; if not then AF1.
3. System checks if current_pos = upper end position to Analyse; if not AF2.
4. System reads the amount of liquid on the plate; if not enough liquid to perform the analysis AF3.
5. Analyser performs the analysis if still allowed to analyse; if not then AF4.
6. System reads the amount of liquid on the plate; if the analysis was not performed ok then AF5.
7. Signal analysis_ok.

Failure reports:

AF1. No plate is present in the Analyser.
Remedy: User loads the Analyser manually and resumes or aborts.

AF2. Current_pos /= upper end position to Analyse.
  Remedy: User moves the Analyser manually to upper end position and resumes or aborts.

AF3 There is not enough liquid on the plate.
  Remedy: User finds out the reason of the situation and resumes or aborts the calling protocol. In case of resuming: user manually loads liquid and resumes protocol.

AF4. Erroneous analysis command. Protocol failure.
  Remedy: Check and change protocol or abort.

AF5. Failure in analysis, the analysis did not use the right amount of liquid.
  Remedy: User initiates a maintenance procedure to fix the pump precision. After maintenance user resumes or aborts protocol.

Subroutine Deliver captures the delivering of a plate to the Robot, provided the operating table is at its lower end position and there is a plate in the Analyser.

Typical course of events:

1. Analyser receives command *deliver* from protocol.
2. System checks if Robot is ready for plate; if not then DF1.
3. System checks if current_pos = lower end position to Deliver; if not DF2.
4. System checks if a plate is present; if not then DF3.
5. Robot unloads the Analyser.
6. System checks if plate has been delivered; if not then DF4.
7. Signal delivery_ok.

Failure reports:

DF1. Robot is not ready to unload the Analyser.
  Remedy: Wait a while for the Robot to become ready.

DF2. Current_pos /= lower end position to Deliver.
  Remedy: User identifies the cause and moves the Analyser manually.

DF3. Plate is not present.
  Remedy: User identifies the cause, and loads the Analyser manually or aborts.

DF4. The Analyser has not been unloaded.
  Remedy: User identifies the cause, unloads the Analyser manually and resumes or aborts.

Failures:

From the alternative courses of events above we can derive the following failures:

a) Analyser move failure
b) No plate present
c) Plate already present

d) Analysis failure
e) Robot rotate failure
f) Robot arms move failure
g) Robot arms gripper failure
h) Protocol failure

Upon having this reasonably grained use case based specification, the next step is to determine the logically related use cases, and group them together. Each group of related use cases defines (informally still) a control system *component*.

4.2 Component-oriented development

Component-oriented development consists of reusing existing components, developing new components, and assembling new systems from them. A component is usually defined as a black box implementing a set of services, provided that the required set of context dependencies are available. A component is thus an abstraction over the space of services of a system. The services that a system has to perform, captured by the use case diagram, are partitioned into groups, each group of services being eventually implemented by a component. Components interact with each other by using the provided services. Thus, an important issue regarding a component-based system is the interactions among the participating components as shown in Fig. 5.

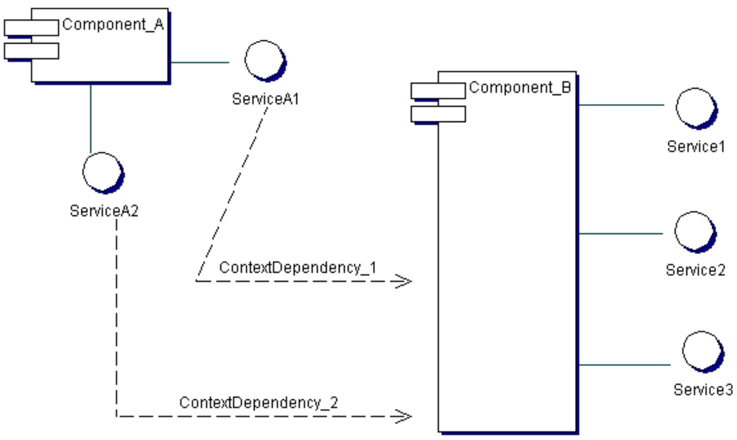

Fig. 5: Components

By defining a set of components of the final system we distribute the computation already in this early development stage. The strategy of separating computation and communication from the beginning supports well reuse and scalability. A subset of the eventual system components may already exist and can be reused. Each of the unimplemented components is a self-contained system of finer granularity than the initial system. Therefore, the process of specifying a system is reduced to specifying each defined, but not yet implemented component, encompassing the communication means with other components. The resulting specification models the necessary conceptual model of the component required for providing the component services.

The component diagram is deduced from the use case diagram, and the component interactions are deduced from the use case relationships. Each use case can be mapped to a component service. While the use case diagram shows only the required services and their relationships, the component diagram distributes the services to a set of components that will implement them. The conceptual model of each component, required for providing these services, is typically specified in a precise manner, using a certain specification language. We use the B-action systems to express the component specifications. Each component is modeled as one or more machines within the B Method. The services of the component are operations in the machine.

In our case study the functional requirements of the Analyser are to receive plates which are being analysed and then delivered to an external device, the Robot. From the use case diagram in Fig. 4 we can construct an associated component diagram as given in Fig. 6. We are only interested in the Robot loading and unloading the Analyser. The rest of the services of the Robot are only given as ‘other services’.

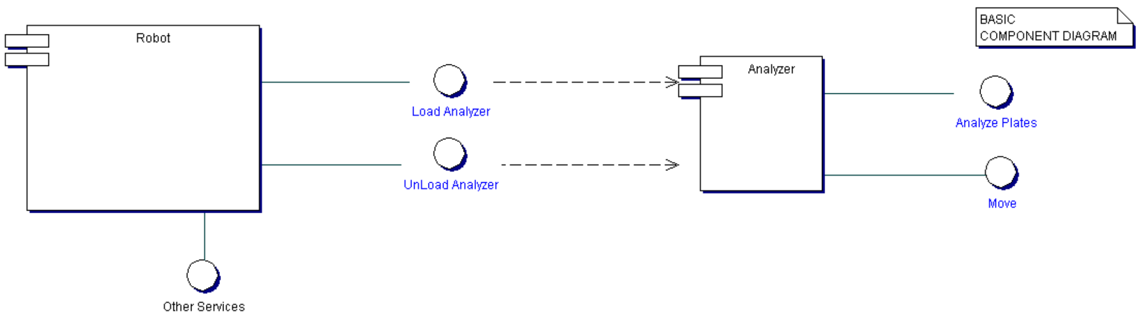

Fig. 6: A Component Diagram for the analysing device.

4.3 Statechart diagrams

At this level, the conceptual model of the component is shown as one active class, i.e., a class whose instances have autonomous behavior. The class has typically several attributes and methods and the autonomous behavior is specified using statechart diagrams. At least three such statechart diagrams are developed.

The first primitive statechart diagram is shown in Fig. 7. The services in this statechart diagram are derived from the services in the use case diagrams. Here we merely model state transitions and events causing these transitions. We go from state

Idle to a service *n* or to state *Suspension*. After service *n* is performed we return to state *Idle* or go to state *Suspension*. From state *Suspension* we may return to service *n* or to state *Idle,* or go to the state *Abort.* An attribute named *state* is added to the component's class to model this behaviour.

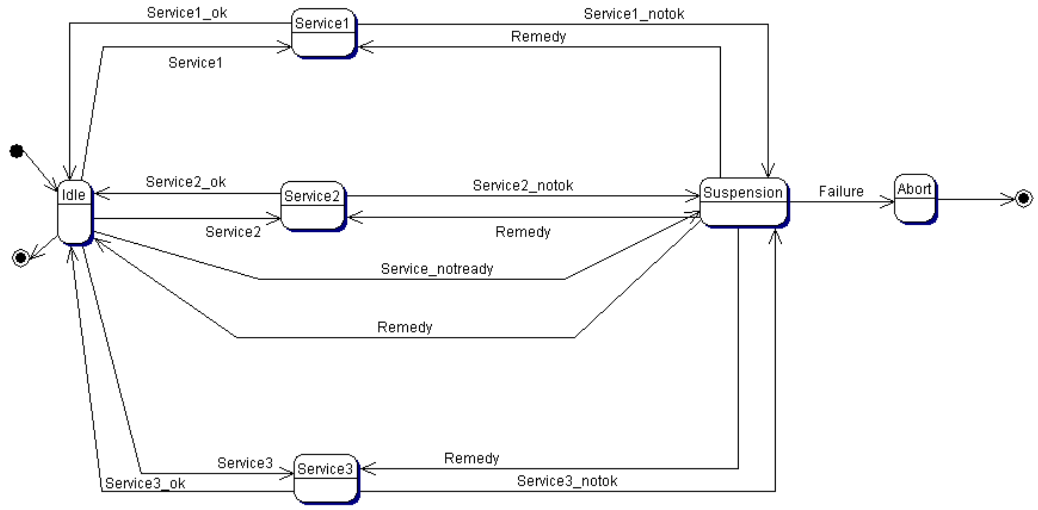

Fig. 7: A basic statechart diagram for a component.

The basic statechart diagram of the Analyser in Fig. 8 can be derived from the use case diagram in Fig. 4. The services *move*, *receive*, *analyse* and *deliver* in the use case diagram form the states in this basic statechart diagram together with the states *idle*, *suspended* and *abort*.

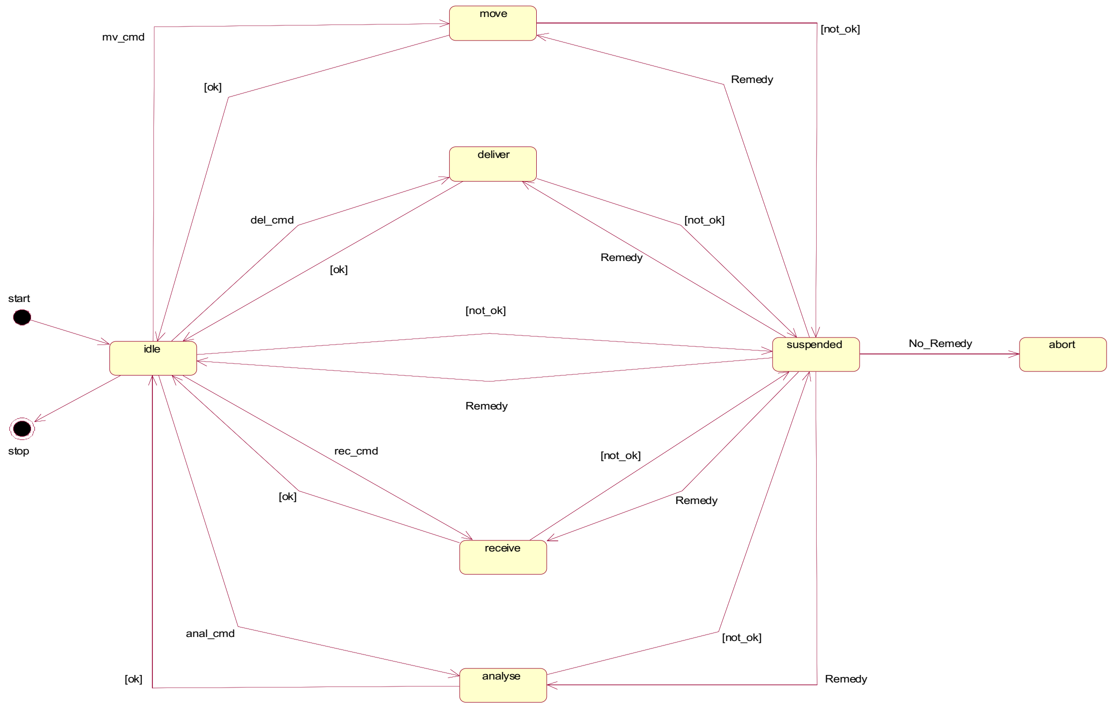

Fig. 8: Basic Statechart Diagram for the Analyser.

Next we state the services of the basic statechart with more details in a refined statechart diagram. The refined statechart diagram presented in Fig. 9 shows the component evolving from a state *Idle* to states performing each of the required services, provided certain conditions, *ServiceN_prec*, are satisfied. If these services are successfully performed, when *ServiceN_postc* holds, the component returns to its state *Idle*. An exception of a service suspends the autonomous behavior of a component, that evolves to the state *Suspension*. If a remedy of an occurred exception is found, the component can resume its service-providing state. If no remedy exists, then the exception is a failure and the component aborts its execution.

The refined statechart diagram is derived from the use case description (subroutine description). All the conditions shown in the diagram are expressions on the class attributes and methods. At this level, the initial informal specification regarding the respective component is completely captured by this refined statechart diagram. This diagram can still be refined to a more detailed statechart diagram involving more attributes and methods.

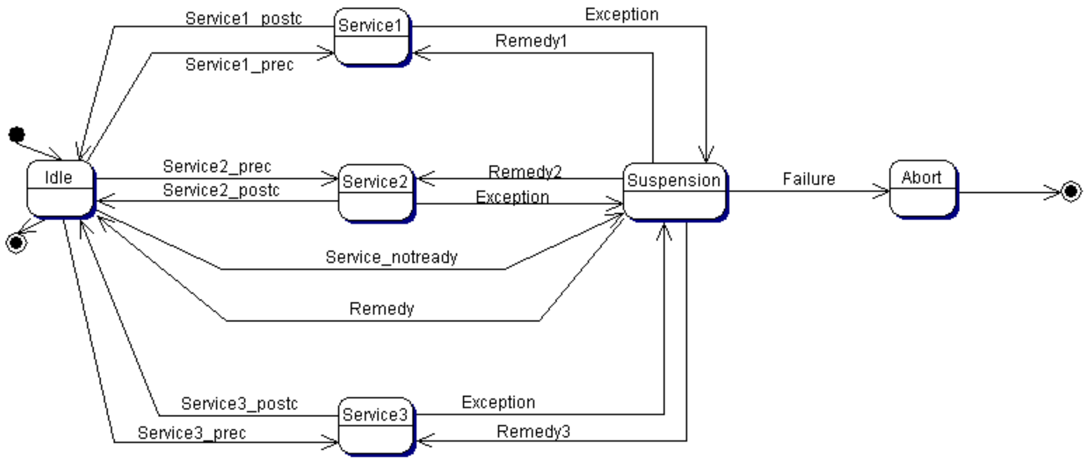

Fig. 9: A refined statechart diagram for a component

A refined statechart diagram of the Analyser can be found in Appendix A. All the subroutines are pictured in this statechart diagram. In order to be able to get a better overview of each subroutine and to capture all the details we would need a separate statechart diagram for each subroutine. The connection between these separate diagrams would then need to be explicitly stated. This is still ongoing work within the healthcare case study.

5. B-action systems in the development

While we can guarantee the consistency of the first statechart diagram in Fig. 7, due to its basic patterns and simplicity, a more complex diagram is not obviously shown to be consistent with its specification. For ensuring this, we need a formal analysis tool. A formal method that comes with such tools is the B Method. We rely here on one of the tools supporting it, Atelier B, when performing the development and the proving. In order to be able to reason about distributed systems within the B Method we use B-action systems [WS98] related to Event based B.

5.1 The abstract specification

The first step in our formal development is to create an abstract B-action system from the basic statechart diagram in Fig. 7. The tool U2B [SB00] developed within the MATISSE project at Southampton University supports this translation. The event triggering state transitions (names assigned to arrows) correspond to operation names in the abstract machine specification below.

```
MACHINE Component
VARIABLES
        state, cmd
INVARIANT
        state : {Idle,Service1,Service2,Service3,Suspension,Abort} /\
            cmd : {serv1,serv2,serv3}
INITIALISATION
        state := Idle || cmd :: {serv1,serv2,serv3}
OPERATIONS
        New_command(ss) = PRE ss : {serv1,serv2,serv3} THEN
                                          SELECT state = Idle  THEN cmd := ss END
                                  END;

        Service1 = SELECT cmd = serv1  /\  state = Idle
                               THEN state := Service1 END;
        Service1_fail =   SELECT cmd = serv1  /\  state = Idle
                               THEN state := Suspension END;
        Service1_ok  =   SELECT state = Service1  THEN state := Idle END;
        Service1_notok = SELECT state = Service1  THEN state := Suspension END;
        …
        Service_notready =  SELECT state  = Idle THEN state := Suspension END;
        Remedy =      SELECT state = Suspension
                      THEN state :: {Idle,Service1,Service2,Service3} END;
        Failure =              SELECT state = Suspension THEN state := Abort END
END
```

The B-action system is identified by a unique name, *Component.* The attributes/variables of the system are given in the **VARIABLES**-clause. In the basic statechart diagram the attribute *state* and the attribute *cmd* corresponding to *Service*N form the variables of the system. The types and the invariant properties of the local variables are given in the **INVARIANT**-clause and their initial value in the **INITIALISATION**-clause. The operations/services on the variables are given in the **OPERATIONS**-clause. Each service of the basic statechart diagram will have four operations: the first for checking its precondition, the second for taking care of a false precondition, the third for executing the proper result of an operation and the fourth for taking care of a failed computation. We also have an operation *Remedy* for fixing an exception and continuing the computation, and an operation *Failure* taking the system to the state *Abort* from where no further execution is possible.

With this B-action system we model parallel and distributed systems, where operations are selected for execution in a non-deterministic manner. The operations are given in the form Oper = SELECT P THEN S END, where *P* is a predicate on the variables (also called a guard) and *S* is a substitution statement. When *P* holds the operation *Oper* is said to be enabled. Only enabled operations are considered for execution. When there are no enabled operations the system terminates. The operations are considered to be atomic, and hence, only their input-output behaviour is of interest.

In B-action systems we can also have global variables that can be read and updated by more than one system. The global variable is declared in a separate machine *Global_z* which is **INCLUDED** in the communicating systems *A_comp* and *B_comp*. By including the machine *Global_z* in *A_comp* and *B_comp,* they are both allowed to assign a value *v* to the variable *z* via the operation *assign_z(v)* [WS98].

```
MACHINE  A_comp
INCLUDES  Global_z
VARIABLES
  …
END
```

```
MACHINE  B_comp
INCLUDES  Global_z
VARIABLES
  …
END
```

```
MACHINE  Global_z
VARIABLES
  z
INVARIANT
  J(z)
INITIALISATION
  z := z0
OPERATIONS
   assign_z(v) = PRE J(v) THEN z := v END
END
```

Previously developed machines that have been shown correct can be used in the development by including them in the component using **SEES**, **INCLUDES** or **EXTENDS** [Abrial96]. We can also have procedures in a B-action system. The procedures declared in a B-action system can be local or exported. The local procedures are declared and referenced locally within the same system. The exported procedures, on the other hand, may be referenced by other B-action systems as well. An exported procedure of one system is an imported procedure of another system. The exported/imported procedures are services provided/claimed between systems (components) and can be derived from the component diagram. Let us consider the exported procedure *P* declared in system *B_comp* and called from system *A_comp* as shown below.

```
MACHINE  A_comp
INCLUDES  B_comp
VARIABLES
   x
INVARIANT
  I(x)
INITIALISATION
  x := x0
OPERATIONS
   A1 = SELECT Q1  THEN T1 || P END;
   …
END
```

```
MACHINE  B_comp
VARIABLES
  y
INVARIANT
  J(y)
INITIALISATION
  y := y0
OPERATIONS
   P = SELECT G THEN U END;
   …
END
```

We note that the B Method requires the calling operation and the procedure to be in separate machines. Hence, in case an operation in *B_comp* also calls the procedure *P*, we have to outsource *P* into a separate machine and incorporate them via the **INCLUDES**-clause. When operation *A1* calls procedure *P*, *A1* is enabled only if procedure *P* is also enabled, i.e., $Q1 \wedge G$ holds. The procedure *P* and the operation *A1* are executed as a single atomic entity. The procedures are discussed in more detail in [Waldén98].

Formal specifications and safety analysis

Our initial specification of the system is rather abstract – it merely models transition between states. However, already in the initial specification we reserve a possibility of fault occurrence and system failure. The actions *Service1_fail* and *Service1_notok* model failure of execution of command.

```
Service1_fail =       SELECT cmd = serv1  /\  state = Idle THEN state := Suspension END

Service1_notok = SELECT state = Service1  THEN state := Suspension END
```

There is also a possibility of spontaneous fault occurrence even when a service is not requested, as modelled by the action *Service_notready*.

```
Service_notready =  SELECT state  = Idle THEN state := Suspension END
```

In all actions presented above the system reacts on fault occurrence by entering state *Suspension*. From that state the system tries to execute a recovery procedure and continue functioning as specified by the action *Remedy.*

```
Remedy = SELECT state = Suspension THEN state :: {Idle,Service1,Service2,Service3} END
```

When the fault tolerance limit has been reached and the system cannot carry out its functions anymore we have a failure of the system and enter state *Abort*. We model this with the action *Failure*:

```
Failure = SELECT state = Suspension THEN state := Abort END
```

This action represents the transition of the system into a fail-safe state.

Formal specification of the Analyser

From the statechart diagram in Fig. 8 we can get the abstract B-action system *Analyser.mch* given in Appendix B. The Analyser has four services/subroutines *move, receive*, *analyse* and *deliver*. The only variables in this first machine are the variables modeling the states *astate* and the current command *acmd*, as well as a global variable *plate* stating whether there is a plate in the Analyser or not. The global variable is given in the machine *GlobalVar_Plate.mch* in Appendix B.3. The sets of possible states and commands of the Analyser are derived from the basic statechart diagram and given in the machine *def.mch* in Appendix B.2.

The exported global procedures of the Analyser are given in the machine *A_proc.mch* in Appendix B.5 and of the Robot in the machine *R_proc.mch* in Appendix B.4. The exported procedures of the Robot are the imported procedures of the Analyser. The Analyser exports the procedures *ReadyToDeliver,* stating if the Analyser is ready to deliver a plate or not, *ReadyToReceive,* stating if the Analyser is ready to receive a plate or not, as well as *BlankInAnalyser* stating whether the Analyser senses a plate or not. In order for the Analyser to be able to function correctly it checks via the imported procedures whether the Robot is safe or not, *Safe*, whether the Robot has a blank available or not, *Available_blank*, and whether the Robot is ready to receive a blank or not, *ReadyFor_blank.* The exported and imported procedures are modeled as *skip* statements here. These procedures are called from the operations in *Analyser.mch* to model that these requirements need to be considered later in the development. The Robot has to be in a safe state when the Analyser is moving and the plate has to be in the Analyser during an analysis. During the delivery operation the Robot should also be ready to receive the plate that should exist in the Analyser, while the receive operation requires the Robot to have a plate available for the empty Analyser.

The exported procedure *NewCommand* that is not called by the Analyser itself is given in *Analyser.mch* for verification reasons. It assigns a new value to the command variable *acmd.* A new command can be given each time the Analyser is in state *idle*.

5.2 Refining the system

An important feature coming with the B-action systems formalism consists in the possibility of stepwise refining specifications. The refinement as a process is seen as transforming a specification C into a specification C' when C is abstract and non-deterministic and C' is more concrete, more deterministic and preserves the functionality of C. A particular refinement method consists in adding new functionality to a specification, i.e., new variables and substitutions on these, in a way that preserves the old behavior. This type of refinement is referred to as superposition refinement. When dealing with complex control systems it is especially convenient to stepwise introduce details about the system to the specification and not to have to handle all the implementation issues at once.

After translating the basic statechart diagram into a B-action system, we gradually refine the system towards a B-model suggested by the complex statechart diagram. For the refinement process we identify the attributes suggested in the complex statechart diagram and the use case descriptions. These attributes/variables are then added gradually to the specification making it more concrete. At each refinement step we add one or more variables. For each variable we state the safety conditions and the properties of the variable that can be found in the requirements specification. We add the computation concerning the new variable(s) to the existing operations. New operations that only assign the new variable(s) may also be added.

```
REFINEMENT Component _Ref
REFINES Component
VARIABLES
      variable_list
INVARIANT
      variable_types /\
      variable_relations /\
      variable_requirements
INITIALISATION
      variable_initialisation
OPERATIONS
      New_command(ss) = PRE ss : {serv1,serv2,serv3} THEN
                                          SELECT state = Idle  THEN cmd := ss END
                                END;

      Service1 =        SELECT Service1_prec  /\  state = Idle
                         THEN state := Service1 || Service1_comp END;
      Service1_fail =   SELECT ¬ Service1_prec  /\ state = Idle
                         THEN state := Suspension1 END;
      Service1_ok  =    SELECT Service1_postc  /\ state = Service1
                         THEN state := Idle || Service1_endcomp END;
      Service1_notok = SELECT ¬ Service1_postc  /\ state = Service1
                         THEN state := Suspension1 END;
      Remedy1 =         SELECT state = Suspension1
                         THEN fix _the_error1  || state := Service1 END;
      …
      Services_notready =   SELECT state = Idle THEN state := Suspension END;
      Remedy =              SELECT state = Suspension
                             THEN fix _the_error  || state := Idle END;
      Failure =             SELECT state : {Suspension,Suspension1,…,Suspension3}
                             THEN state := Abort END
END
```

The refinement *Component_Ref* of the machine *Component* can be derived from the state diagram in Fig. 9. It has a list of variables in its **VARIABLES**-clause where some of the variables did not exist in the abstract machine *Component*. The types of the variables, their properties and internal relations as well as their safety requirements are given in the **INVARIANT**-clause. The variables are updated in the operations. Compared to the abstract machine specification *Component* the refinement machine has more detailed operations. The guards have more precise conditions under which the operation can be performed and also the newly introduced variables can be changed in the operation. In the operation *Service1* below the new variable(s) are referenced to in the predicate *Service1_prec* as well as in the substitutions in *Service1_comp*. Furthermore, new operations concerning each service/subroutine may be introduced that take care of new features introduced by the new variables. The exported procedures are incorporated in the system as before.

Safety issues during the refinement

As the system development proceeds we obtain more elaborated information about faults and conditions of failure occurrence. The refinement step introduces distinction between faults. The operation *Service1_fail* models fault resulted from an attempt to provide a service from an incorrect initial state:

```
Service1_fail =    SELECT ¬ Service1_prec  /\ state = Idle THEN state := Suspension1 END
```

This situation might be caused by faults occurred previously or by a logical error in the calling command. The operation *Service1_notok* models fault occurrence during the execution of the action:

```
Service1_notok = SELECT ¬ Service1_postc  /\ state = Service1 THEN state := Suspension1 END
```

These kinds of faults are caused by the physical failures of the system components involved in the execution.

We also introduce a distinction between different repair procedures by adjusting the *Remedy* operation for each fault accordingly.

The action *Failure* models system shut down:

```
Failure =     SELECT state : {Suspension,Suspension1,…,Suspension3} THEN state := Abort END
```

The action becomes enabled when the attempts to fix occurred faults fail.

Safety analysis proceeds by an identification of different failure modes of the system. It is conducted by considering the consequences of multiple faults. In the system specification we proceed by specifying statuses of components (failed or functioning), specifying system failure modes and finally by introducing error messages.

The first refinement step of the Analyser

The statechart diagram in Appendix A gives a UML view of the refined Analyser. The requirements give a hint of the variables to be introduced during the refinement. The first refinement of the Analyser *Analyser1.ref* is given in Appendix C. In this refinement step we introduce details on moving the operating table up and down, as well as on the presence of the plate on the operating table. We add a variable *blank* modeling the Analyser sensing whether it contains a plate (*TRUE*) or not (*FALSE*). Furthermore, the Analyser keeps track of its operating table position (z*max*, z*mid*, z*min*) using the variable *zpos*. The variable has the value *zmax* at the upper end position when analysing, *zmin* at the lower end position when delivering a plate to and *zmid* at the middle position when receiving a plate from the Robot. The variables *zpos* and *blank,* as well as the procedures changing their values are given in the procedure machine *A_proc1.mch* in Appendix C.3.

In the refinement we also keep track of how many times the operaing table has moved before interacting with the Robot, *move_counter*, as well as the number of analyses to the current plate, *analyse_counter*. The maximum numbers of moves and analyses are restricted by *aMaxMoves* and *aMaxAnalyse*, respectively. We also introduce a boolean variable, *awaited*, simulating the Analyser waiting for the Robot to finish its tasks. In the refined Analyser a new command can be given in the state *idle* only if *awaited* has the value *FALSE* (the Analyser is not waiting). The "adminstrative" variables *move_counter*, *analyse_counter* and *awaited* can be found in the main machine *Analyser1.ref* in Appendix C.1.

The operations and procedures of the Analyser are updated to reflect the changes of the new variables. The operations *MoveA*, *Receive, Analyse* and *Deliver* model the subroutines *move*, *receive*, *analyse* and *deliver* of the Analyser. The subroutines are described in detail in Section 4.1. For each subroutine all possible failures are taken into account. If possible, a remedy is given for each failure. The external procedure *ReadyToDeliver* checks if the Analyser contains a plate and has the operating table in position *zmin*, while *ReadyToReceive* checks if the Analyser does not contain a plate and has the operating table in position *zmid*. The procedures *BlankInAnalyser* and *NoBlankInAnalyser*, respectively, check if the Analyser contains a plate or not.

The invariant shows the relation between the states and the commands of the Analyser and the variables *blank*, *zpos* and *awaited*. We can note that the *asuspended* state is divided into several states; *asuspended1*, *amsuspended1*, *aasuspended1*, *arsuspended1*, and *aduspended1*. This is done in order to be able to create more accurate remedy operations for returning to the right state; *aidle1*, *amove1*, *aanalyse1*, *areceive1* and *adeliver1*, respectively. Due to these new suspension states we rename the state variable *astate1* and give its relation to *astate* in the invariant. The updated states are given in the machine *def1.mch* in Appendix C.2.

The second refinement step of the Analyser

As a second refienement step we introduce details on the analysis. The refined system *Analyser2.ref* is given in Appaendix D.1. We add the variable *pl_liq* to keep track of the current amount of liquid on the plate. A certain amount of liquid *anl_liq* is needed in the plate for the analysis to be performed. In order to be able to check the liquid amount used during the analysis we also add a variable *pl_liq_tmp* that records the amount of liquid before the analysis. The constants *anl_liq* as well as *pmax,* the maximum capacity of the plate, concern only the liquid and are given in the machine *Liq_def.mch* in Appendix D.3. The variable *pl_liq* is added to the procedures machine *A_proc2.mch* in Appendix D.2 together with the procedures that update it. The operations in *Analyser2.ref* concerning the subroutine *analyse* are updated to take the liquid amount into account. The invariant is updated to state that if there is no plate in the Analyser (*blank* = *FALSE*) the liquid amount is zero (*pl_liq* = *0*).

5.3 Proving the correctness of the refinement

Within Atelier B we can actually prove formally that the refinement is sound. For this a number of proof obligations first need to be generated. Let us assume that we have two systems *A_comp* and *C_comp* as below. The variable *x* is a variable of both *A_comp* and *C_comp.* In the refinement step the variable *y* is a new variable of *C_comp*. The operations *A1*, *A2* and *A3* are changed to also take *y* into account in *C_comp*. The operations *B1* and *B2* are created during the refinement step.

```
MACHINE A_comp
VARIABLES
  x
INVARIANT
  Inv_A
INITIALISATION
  x := x0
OPERATIONS
   A1 =  SELECT P1  THEN S1 END;
   A2 =  SELECT P2 THEN S2 END;
   A3 =  SELECT P3  THEN S3 END
END
```

```
REFINEMENT C_comp
REFINES A_comp
VARIABLES
  x, y
INVARIANT
  Inv_C
INITIALISATION
  x := x0 ||  y:= y0
OPERATIONS
   A1 =  SELECT P1'  THEN S1' END;
   A2 =  SELECT P2' THEN S2' END;
   A3 =  SELECT P3' THEN S3' END;
   B1 =  SELECT Q1  THEN T1 END;
   B2 =  SELECT Q2 THEN T2 END
END
```

The proof obligations needed for proving that a concrete system *C_comp* is a correct refinement of a more abstract system *A_comp* are as follows [BS96, WS98]:

1. The initialization in *C_comp* should be a refinement of the initialization in *A_comp*, and the initialization should establish the invariant *Inv_C*.
2. Each operation *Ai* (i=1,2,3) in *C_comp* should refine the corresponding operation (the operations with the same name) in *A_comp*, and they should preserve the invariant *Inv_C.*

3. Each new operation *Bj* (j=1,2) in *C_comp* (that do not have a corresponding operation in *A_comp*) should only concern the new variable *y*, and preserve the invariant *Inv_C*.
4. The new operations *Bj* (j=1,2) in *C_comp* should terminate, if they are executed in isolation.
5. Whenever an operation *Ai* (i=1,2,3) in *A_comp* is enabled, either the corresponding operation *Ai* in *C_comp* is enabled or then one of the new operations *Bj* (j=1,2) in *C_comp* is enabled.
6. Whenever a fault occurs in *A_comp* (a fault-operation in *A_comp* is enabled), a fault could also occur in *C_comp* (a fault-operation in *C_comp* could be enabled).

With the fault-operations in (6.) we mean the operations leading to a *suspension* state. Hence, according to (6.) a general fault is partitioned into distinct faults during the refinement process.

The proof obligations (1.)–(3.) above are automatically generated by Atelier B. Proof obligations (5.) and (6.) can be generated automatically if an *exit*- as well as an *exitFail*-operation are added to the system. The *exit*-operation should be enabled when all the other non-failure operations in the system are not enabled. In *A_comp* the *exit*-operation would be SELECT $\neg P1 \wedge \neg P2 \wedge \neg P3$ THEN skip END. The *exitFail*-operation can be created similarly with the guards of the fault-operations. The proof obligation (4.) requires a variant that is decreased by the new operations. Using Atelier B we need to introduce some additional machine constructs discussed in [Waldén98]. With the help of the Evt2b translator [ClearSy01] also proof obligation (4.) can be generated automatically as discussed in [BW96].

During the refinement process global procedures, procedures that are declared in one system and called from other systems as *P* above, are refined in the same way as the operations of the system. Hence, let us assume that we have an abstract system *A_comp* with a global procedure *P* and a refined system *C_comp* with the refined procedure *P'*. Then for *C_comp* to be a refinement of *A_comp*, the six proof obligations concerning refinement of distributed systems given earlier should hold, as well as:

7. Procedure *P* in *A_comp* should be refined by the corresponding procedure *P'* in *C_comp*, and *P'* should also preserve the invariant.
8. If procedure *P* is enabled so should *P'* be, or then the operations in *C_comp* should enable *P'*.

Proof obligation (7.) is automatically generated by Atelier B, while obligation (8.) requires some extra constructs to be created. For more information on procedures and their proof obligations, see [Waldén98].

The proof obligations can be discharged with the help of the autoprover and interprover in Atelier B. The autoprover uses a database of proof rules in order to perform the proofs. In case the needed proof rules are not found in this database, some new rules can be added via the interprover of Atelier B. The proof obligations that were not proved automatically can be proven interactively with the interprover.

Proving the refinement steps of the Analyser

In the *first refinement step* the initialisations and the operations have been proved to be correct refinements with the provers in AtelierB. The proof obligations concerning the exit conditions have been proved with the tool as well. Furthermore, we have used the tool to prove that the auxiliary actions will eventually terminate when executed in isolation and that the refined external procedure *NewCommand* in *Analyser1.ref* will eventually be enabled if the procedure *NewCommand* in *Analyser.mch* is enabled. The other external procedures in the Analyser consist of a guard *g* and a *skip* statement. For each of these procedures a failure procedure is given with the dual guard *not(g)*. Hence, one of these procedures is always enabled in the refined system *Analyser1.ref* as is the case for the procedure *skip* in *Analyser.mch*.

Proving the correctness of the *second refinement step* only involves proving that the initialisation establishes the invariant and that the operations and exported procedures preserve it. Also the exit conditions for this refinement step are easily proved with the provers of Atelier B. The other proof obligations are trivial since no new operations are introduced and the new functionality only concerns the operations of the subroutine *analyse*.

In this way we have obtained a B-specification of the component that is consistent with the informal, initial system specification. In parallel, we have the UML statechart diagrams as a graphical documentation of the B-specification, since we keep the two specification models consistent with each other. Once the refinement is proved for the B-action systems, we update the statechart diagrams to be consistent with the formal model. The updating of the UML diagrams is still done manually.

6. Control system development

A control system is usually a complex system consisting of several components that interact with each other, like the Analyser and the Robot in our case study. In the second phase of the control system development each component will be decomposed to control system modules.

6.1 Component communication

Statechart diagrams are quite suitable for modeling control system components, due to the reactive nature of the latter. However, a statechart diagram describes the autonomous behavior of one entity, and we have presumably several components, that interact with each other. The communication between these components is modeled by events, see for example, *CD2_event1, CD1_event5* in Fig. 10. These events trigger various transitions between states.

An event is either synchronous (a procedure call) or asynchronous (a signal), or models the passing of time or the fulfillment of a boolean expression. The most typical event we use to model the components communication is the signal. Signals are modeled as global variables in B-action systems. Procedure calls and global variables in B-action systems are discussed in section 5.1.

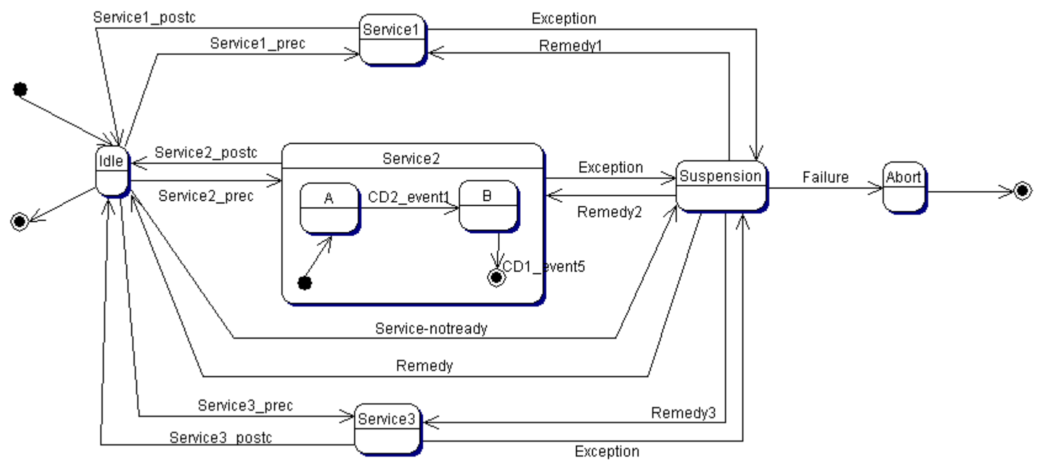

Fig. 10: Refinement of state *Service2*

6.2 Decomposition of the system

The second phase of the development process consists in decomposing each component's B-specification into control system modules. We perform this decomposition for each component, keeping their communication patterns with each other intact, as well as proving the distribution to be sound with respect to the centralized specification.

In B-action systems two components *A_comp* and *B_comp* can be composed to a parallel system, denoted *A_comp*||*B_comp*. This composition is formed by merging the variables, procedures and operations of the components *A_comp* and *B_comp*. The local variables of the components have to be distinct. Let us consider the components

A_comp and *B_comp* below, where *x* and *y* are local variables and *u,v* and *z* are global variables. The global variable *z* is a common variable of *A_comp* and *B_comp*. The other variables are distinct.

```
MACHINE  A_comp
INCLUDES
  Global_u, Global_z
VARIABLES
  x
INVARIANT
  Inv_A
INITIALISATION
  x := x0
OPERATIONS
  A_oper =  SELECT P  THEN S END
END
```

```
MACHINE  B_comp
INCLUDES
  Global_v, Global_z
VARIABLES
  y
INVARIANT
  Inv_B
INITIALISATION
  y:= y0
OPERATIONS
  B_oper =  SELECT Q  THEN T END
END
```

The *parallel composition A_comp||B_comp* of the components *A_comp* and *B_comp* is then defined as the abstract machine *A_comp||B_comp* below.

```
MACHINE  A_comp||B_comp
INCLUDES
  Global_u, Global_v, Global_z
VARIABLES
  x, y
INVARIANT
  Inv_A /\ Inv_B
INITIALISATION
  x := x0 || y := y0
OPERATIONS
  A_oper =  SELECT P  THEN S END;
  B_oper =  SELECT Q  THEN T END
END
```

The variables and the initialization, as well as the operations in *A_comp* and *B_comp* are simply merged to form *A_comp||B_comp.* The operations from the components *A_comp* and *B_comp* are executed in an interleaving manner. In case *A_comp* and *B_comp* would have procedures they would be merged in the same way as the variables. This rule can be applied in reverse and is then called *parallel decomposition*. More on this topic can be found in [BW96].

6.3 Hardware/software co-design

The initial development phase of a control system produced a model of the overall system consisting of several components, like the Analyser and the Robot in our case study. Each component eventually implements a group of related services and has a B-specification corresponding to a UML model. The UML model of the component is typically formed of one class diagram and several statechart diagrams, while the B-specification is formed of possibly several machines.

In the second development phase, each component is distributed into control system modules, *plant*, *controller*, *sensors* and *actuators*, as shown in Fig. 11. Technically, the B-specification of the component is stepwise refined using the superposition refinement rule together with the parallel decomposition rule for B-action systems. The number and type of the specific control system entities are determined during this phase of the development. The second development phase is studied in more detail in report [PRTWJ01].

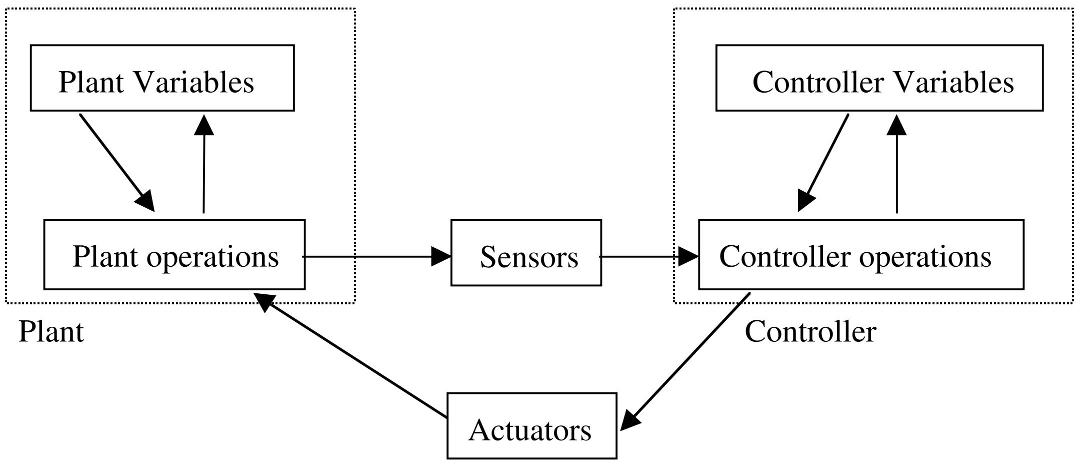

Fig. 11: The structure of the control system specification

7. Conclusion

The field of computer science has developed at an incredible pace in the last years, leading to an omnipresence of the software-based technology in almost every domain. The software systems that are currently required are characterized by a great increase in the software size, a shift in the software application areas, as well as by the need of software reuse, smoother evolution, and timely development.

As reliability of software applications is now a central concern, we witness an increased need for a better balance between the theoretical and the practical sides of computer science. *Practical* computer science, i.e., the science of constructing software, should be based on a more stable *theoretical* basis, to make it more deterministic and more reliable. In turn, the current *theoretical* aspects of the software engineering should be enhanced so that they are able to scale up. Ultimately, the goal of the software industry is to have a tool-assisted, well-defined software development process that includes safety and correctness evaluation of the deliverables and is usable in a timely fashion, i.e., it is predictable.

Our proposed process is as follows:

1. cover as much as possible of the development life cycle by formal methods,

2. integrate informal and formal languages and methods, most notably UML, safety analysis and B including tool support for this,

3. integrate the produced specifications and code with other in-house code used in the device if necessary.

We consider that the combination of UML, safety analysis, and B will facilitate the acceptance of formal methods in general for industrial use.

Acknowledgement

The authors would like to thank Kaisa Sere for her useful comments on the topics treated here.

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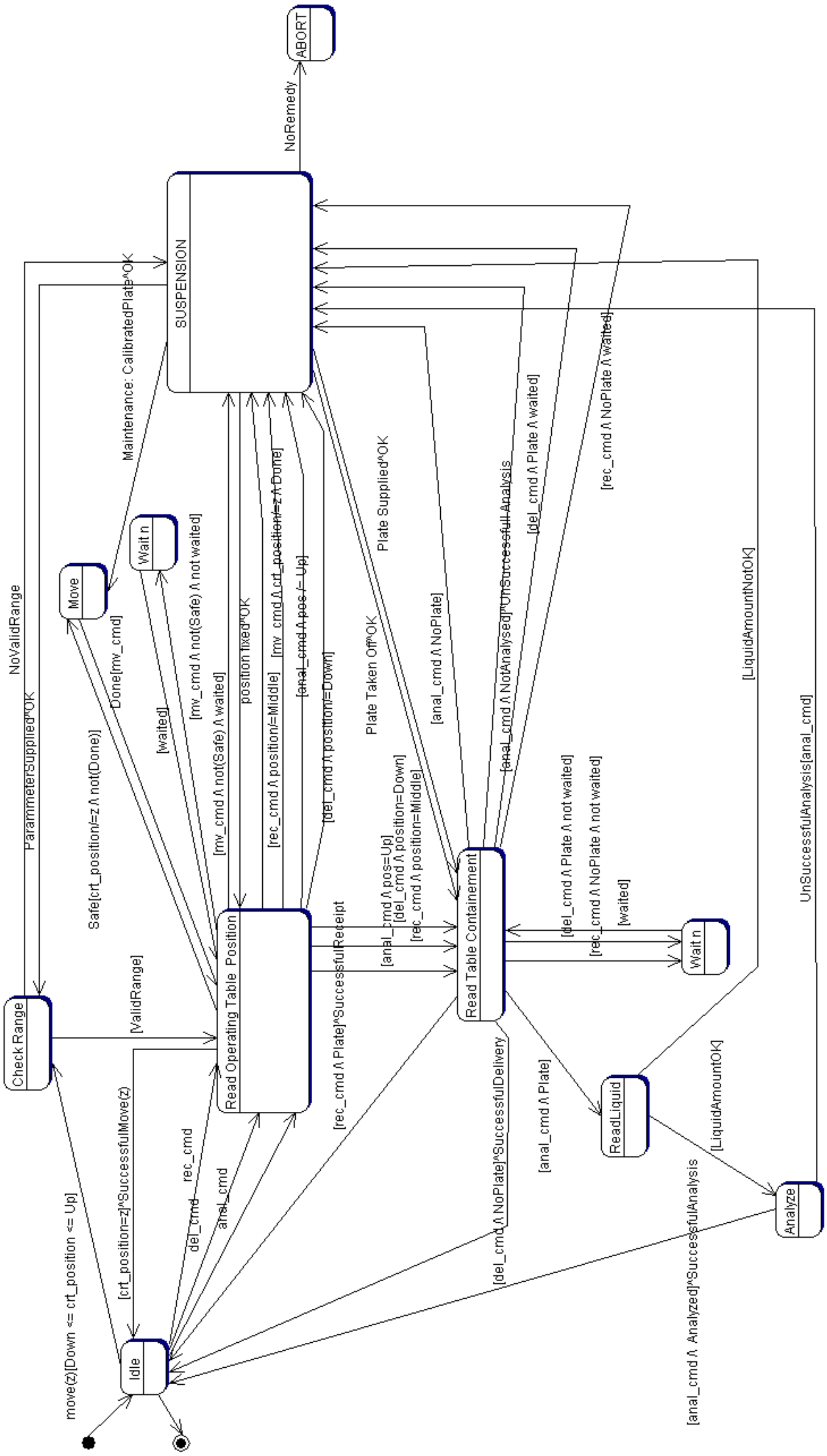
Appendix A: Statechart diagram of the Analyser



Appendix B:
The specification of the Analyser as B-action systems

B.1 The specification of the Analyser Analyser.mch

We give the abstract specification of the Analyser in *Analyser.mch*. The operations that will be included in the next step are here given as skip operations. This machine is derived from the basic UML statechart-diagram.

The variables of the abstract system are *astate* and *acmd* modeling the state of the Analyser and the command given to the Analyser, respectively.

```
MACHINE
      Analyser
SEES
      def
INCLUDES
      GlobalVar_Plate,R_proc,A_proc
VARIABLES
      astate,acmd
INVARIANT
      astate:ASTATE &
      acmd:ACOMMAND &
      (astate=amove    => acmd=move) &
      (astate=aanalyse => acmd=analyse) &
      (astate=adeliver => acmd=deliver) &
      (astate=areceive => acmd=receive) &

      (acmd=move    => astate:{aidle,amove,asuspended,aabort}) &
      (acmd=analyse => astate:{aidle,aanalyse,asuspended,aabort}) &
      (acmd=deliver => astate:{aidle,adeliver,asuspended,aabort}) &
      (acmd=receive => astate:{aidle,areceive,asuspended,aabort}) &

      (astate=aanalyse => plate=TRUE)
INITIALISATION
      astate:=aidle  ||  acmd:=receive
OPERATIONS
      NewCommand(cc)=
            PRE  cc:ACOMMAND  THEN   SELECT  astate=aidle  THEN  acmd:=cc  END   END;

            /* move to position 'pos' */
      MoveA(pos)=
            PRE     pos:NAT
```

```
        THEN        SELECT  astate=aidle & acmd=move
                    THEN   Safe || astate:=amove END  END;

        /* failure - the Robot was not Safe */
    MoveAFail=
        SELECT   astate=aidle & acmd=move  THEN  NotSafe || astate:=asuspended   END;

    MoveAMinRemedy=
        SELECT   astate=asuspended & acmd=move  THEN   Safe || astate:=aidle   END;

    MoveAMidRemedy=
        SELECT      astate=asuspended & acmd=move  THEN   Safe || astate:=aidle   END;

        /* the Analyser has reached the position 'pos' */
    MoveAReady(pos)=
        PRE     pos:NAT
        THEN    SELECT  astate=amove & acmd=move  THEN    astate:=aidle END END;

        /* the Analyser  has not reached the position 'pos' */
    MoveANotReady(pos)=
        PRE     pos:NAT
        THEN        SELECT  astate=amove & acmd=move
                    THEN    astate:=asuspended END   END;

        /* fix the problem */
    MoveRemedy(pos)=
        PRE  pos:NAT
        THEN        SELECT  astate=asuspended & acmd=move
                    THEN    Safe || astate:=amove    END    END;

/*************************************************************/
        /* Analyse the plate */
    Analyse=
        SELECT  astate=aidle & acmd=analyse
        THEN        PlateInAnalyser || astate:=aanalyse       END;

        /* general failure */
    AnalyseFail=
        SELECT  astate=aidle & acmd=analyse  THEN    astate:=asuspended   END;

        /* failure - no plate in Analyser */
    AnalysePlateFail=
        SELECT  astate=aidle & acmd=analyse
        THEN    NoPlateInAnalyser  ||  astate:=asuspended  END;

    AnalysePosRemedy=
        SELECT    astate=asuspended & acmd=analyse  THEN   Safe || astate:=aidle   END;

    AnalyseMaxRemedy=
        SELECT    astate=asuspended & acmd=analyse  THEN   Safe || astate:=aidle   END;
```

```
        /* the analysis is done */
    AnalyseReady=
        SELECT  astate=aanalyse & acmd=analyse  THEN    astate:=aidle   END;

        /* failure - the analysis has not been done */
    AnalyseNotReady=
        SELECT  astate=aanalyse & acmd=analyse  THEN    astate:=asuspended   END;

        /* fix the problem */
    AnalyseRemedy=
        SELECT  astate=asuspended & acmd=analyse
        THEN    PlateInAnalyser || astate:=aanalyse   END;

/**************************************************************/
        /* deliver a plate to the Robot */
    Deliver=
        SELECT  astate=aidle & acmd=deliver
        THEN    PlateInAnalyser || ReadyFor_blank || astate:=adeliver  END;

        /* general failure */
    DeliverFail=
        SELECT  astate=aidle & acmd=deliver  THEN    astate:=asuspended  END;

        /* failure - no plate to deliver */
    DeliverPlateFail=
        SELECT  astate=aidle & acmd=deliver
        THEN    NoPlateInAnalyser || astate:=asuspended  END;

        /* failure - the Robot is not ready */
    DeliverFailAtRobot=
        SELECT  astate=aidle & acmd=deliver
        THEN    NotReadyFor_blank || astate:=asuspended  END;

    DeliverPosRemedy=
        SELECT    astate=asuspended & acmd=deliver  THEN    Safe || astate:=aidle  END;

        /* plate delivered ok */
    DeliverReady=
        SELECT  astate=adeliver & acmd=deliver
        THEN  NoPlateInAnalyser || astate:=aidle  END;

        /* general 'plate delivery not ok' */
    DeliverNotReady=
        SELECT  astate=adeliver & acmd=deliver  THEN    astate:=asuspended  END;

        /* failure - there is still a plate in the Analyser   */
    DeliverNotReadyPlate=
        SELECT  astate=adeliver & acmd=deliver
        THEN    PlateInAnalyser || astate:=asuspended   END;
```

```
        /* fix the problem */
    DeliverRemedy=
        SELECT  astate=asuspended & acmd=deliver
        THEN    Safe||NoPlateInAnalyser || astate:=adeliver  END;

/*************************************************************/
        /* receive a plate from the Robot */
    Receive=
        SELECT  astate=aidle & acmd=receive
        THEN    NoPlateInAnalyser || Available_blank || astate:=areceive  END;

        /* general failure */
    ReceiveFail=
        SELECT  astate=aidle & acmd=receive  THEN    astate:=asuspended  END;

        /* failure - there is already a plate in the Analyser  */
    ReceivePlateFail=
        SELECT  astate=aidle & acmd=receive
        THEN    PlateInAnalyser || astate:=asuspended  END;

        /* failure - there is no plate available from the Robot */
    ReceiveFailAtRobot=
        SELECT  astate=aidle & acmd=receive
        THEN    NoAvailable_blank || astate:=asuspended  END;

    ReceivePosRemedy=
        SELECT    astate=asuspended & acmd=receive   THEN  Safe || astate:=aidle  END;

        /* plate received ok */
    ReceiveReady=
        SELECT  astate=areceive & acmd=receive
        THEN    PlateInAnalyser || astate:=aidle  END;

        /* plate not received properly */
    ReceiveNotReady=
        SELECT  astate=areceive & acmd=receive   THEN    astate:=asuspended  END;

        /* failure - the Analyser  has not got a plate */
    ReceiveNotReadyPlate=
        SELECT  astate=areceive & acmd=receive
        THEN    NoPlateInAnalyser || astate:=asuspended  END;

        /* fix the problem */
    ReceiveRemedy=
        SELECT  astate=asuspended & acmd=receive
        THEN    Safe || PlateInAnalyser || astate:=areceive  END;
```

```
/**********************************************************/
        /* general 'not ready' failure */
    AServiceNotReady=   SELECT astate=aidle THEN astate:=asuspended END;

        /* fix the problem */
    ARemedy=        SELECT   astate=asuspended THEN   astate:=aidle END;

        /* there is no remedy for the problem */
    AFailure=       SELECT  astate=asuspended THEN astate:=aabort END;

/*************************************************************************/
        /* Auxiliary operations in the next refinement step ‘/
    MoveWait= BEGIN   skip END;

    DeliverWait= BEGIN   skip END;

    ReceiveWait= BEGIN   skip END;

        /* More specific failure operations in the next refinement step */
    MoveARangeFail(pos)=
        PRE    pos:NAT
        THEN   SELECT astate=aidle & acmd=move THEN astate:=asuspended END  END;

    MoveANoPosChangeFail(pos)=
        PRE    pos:NAT
        THEN   SELECT astate=aidle & acmd=move THEN astate:=asuspended END  END;

    MoveAMinFail(pos)=
        PRE    pos:NAT
        THEN   SELECT astate=aidle & acmd=move THEN astate:=asuspended END END;

    MoveAMidFail(pos)=
        PRE    pos:NAT
        THEN   SELECT astate=aidle & acmd=move THEN astate:=asuspended END  END;

    AnalysePosFail=
        SELECT  astate=aidle & acmd=analyse THEN astate:=asuspended END;

    AnalyseMaxFail=
        SELECT   astate=aidle & acmd=analyse THEN astate:=asuspended   END;

    AnalyseBlankFail=
        SELECT astate=aidle & acmd=analyse THEN astate:=asuspended END;

    AnalyseBlankRemedy=
        SELECT astate=asuspended & acmd=analyse THEN     astate:=aidle END;

    DeliverPosFail=
        SELECT astate=aidle & acmd=deliver THEN astate:=asuspended END;
```

```
    DeliverBlankFail=
        SELECT astate=aidle & acmd=deliver THEN astate:=asuspended END;

    DeliverBlankRemedy=
        SELECT astate=asuspended & acmd=deliver THEN astate:=aidle END;

    DeliverNotReadyBlank=
        SELECT astate=adeliver & acmd=deliver THEN astate:=asuspended END;

    ReceivePosFail=
        SELECT astate=aidle & acmd=receive THEN astate:=asuspended END;

    ReceiveBlankFail=
        SELECT astate=aidle & acmd=receive THEN astate:=asuspended END;

    ReceiveBlankRemedy=
        SELECT astate=asuspended & acmd=receive THEN astate:=aidle END;

    ReceiveNotReadyBlank=
        SELECT astate=areceive & acmd=receive THEN astate:=asuspended END
END
```

B.2 The sets of the Analyser def.mch

In *def.mch* we define the sets of states and commands used in the Analyser.

```
MACHINE
    def
SETS
    ASTATE={aidle, amove, aanalyse, areceive, adeliver, asuspended, aabort};
    ACOMMAND={move, analyse, deliver, receive}
END
```

B.3 The global variable GlobalVar_Plate.mch

The global variable plate is given in a separate machine *GlobalVar_Plate.mch.*

```
MACHINE
    GlobalVar_Plate
VARIABLES
    plate
INVARIANT
    plate:BOOL
```

```
INITIALISATION
      plate:=FALSE
OPERATIONS
      ChangePlate(bb)=      PRE  bb:BOOL   THEN        plate:=bb  END;

      PlateInAnalyser=      SELECT    plate=TRUE  THEN  skip  END;

      NoPlateInAnalyser=    SELECT    plate=FALSE  THE  skip  END
END
```

B.4 The imported procedures R_proc.mch

The imported procedures from the Robot are given in *R_proc.mch*. These procedures are only given as *skip,* since the Analyser need not be aware of their implementation.

```
MACHINE
      R_proc                /* Global procedures */
OPERATIONS
            /* the Robot is Safe */
      Safe=             BEGIN      skip   END;

            /* th Robot is not Safe */
      NotSafe=          BEGIN      skip   END;

            /* the Robot has a plate available */
      Available_blank=        BEGIN      skip   END;

            /* the Robot does not have a plate available */
      NoAvailable_blank=    BEGIN      skip   END;

            /* the Robot is ready to unload the Analyser */
      ReadyFor_blank=       BEGIN      skip   END;

            /* the Robot is not ready to unload the Analyser */
      NotReadyFor_blank=  BEGIN      skip   END
END
```

B.5 The exported procedures A_proc.mch

The exported global procedures of the Analyser are given in *A_proc.mch.*

```
MACHINE
      A_proc
OPERATIONS
                  /* Global Procedures */
```

```
        /* the Analyser is ready to deliver a plate */
    ReadyToDeliver=       BEGIN      skip   END;

        /* the Analyser  is not ready to deliver a plate */
    NotReadyToDeliver=   BEGIN      skip   END;

        /* the Analyser  is ready to receive a plate */
    ReadyToReceive=      BEGIN      skip   END;

        /* the Analyser  is not ready to receive a plate */
    NotReadyToReceive= BEGIN      skip   END;

        /* the Analyser  senses a plate */
    BlankInAnalyser=      BEGIN      skip   END;

        /* the Analyser  does not sense a plate */
    NoBlankInAnalyser=   BEGIN      skip   END
END
```

Appendix C: The first refinement step of the Analyser

C.1 The refined Analyser Analyser1.ref

The first refinement of the Analyser is given in *Analyser1.ref*. In this step we introduce the administrative variables *awaited*, *move_counter* and *analyse_counter*. These administrative variables state the following:

awaited - has the value TRUE if the Analyser has waited for the Robot in order to be able to co-operate with it,

move_counter - the number of moves performed with the current plate setting,

analyse_counter - the number of analyses performed on the current plate.

We consider more detailed failures in this step and, hence, we need more detailed suspension states. In order to model this we modify the state variable to *astate1* and give its relation to *astate* in the invariant.

```
REFINEMENT
      Analyser1
REFINES
      Analyser
SEES
      def1
INCLUDES
      R_proc, A_proc1, GlobalVar_Plate
VARIABLES
      astate1, acmd, awaited, move_counter, analyse_counter
INVARIANT
       astate1:ASTATE1 &
       awaited:BOOL &
       move_counter:NAT  &  move_counter:0..aMaxMoves &
       analyse_counter:NAT  &  analyse_counter:0..aMaxAnalyse &

       (astate1=aidle1 => astate=aidle) &              (astate=aidle => astate1=aidle1) &
       (astate1=amove1 => astate=amove) &              (astate=amove => astate1=amove1) &
       (astate1=aanalyse1 => astate=aanalyse) &        (astate=aanalyse => astate1=aanalyse1) &
       (astate1=adeliver1 => astate=adeliver) &        (astate=adeliver => astate1=adeliver1) &
       (astate1=areceive1 => astate=areceive) &        (astate=areceive => astate1=areceive1) &

       (astate1:{asuspended1,amsuspended1,aasuspended1,arsuspended1,adsuspended1} =>
                  astate=asuspended) &
       (astate=asuspended =>
                  astate1:{asuspended1,amsuspended1,aasuspended1,arsuspended1,adsuspended1}) &
       (astate1=aabort1   => astate=aabort) &
       (astate1=aanalyse1 => blank=TRUE  & zpos=zmax) &
       (astate1=adeliver1 => blank=FALSE & zpos=zmin) &
       (astate1=areceive1 => blank=TRUE  & zpos=zmid) &
```

```
    (astate1=aasuspended1 => acmd=analyse) &
    (astate1=amsuspended1 => acmd=move) &
    (astate1=adsuspended1 => acmd=deliver) &
    (astate1=arsuspended1 => acmd=receive)

INITIALISATION
    astate1:=aidle1 ||  acmd:=receive  ||  awaited:=FALSE  ||  move_counter,analyse_counter:=0,0

OPERATIONS
    NewCommand(cc)=
        PRE     cc:ACOMMAND
        THEN    SELECT  astate1=aidle1 & awaited=FALSE  THEN  acmd:=cc  END   END;

        /* move to position 'pos' */
    MoveA(pos)=
        PRE     pos:NAT
        THEN        SELECT  astate1=aidle1 & acmd=move & move_counter<aMaxMoves
                    THEN    Safe; I nRange(pos); MoveZ(pos); astate1:=amove1;
                                awaited:=FALSE; move_counter:=move_counter+1
                    WHEN    astate1=aidle1 & acmd=move & move_counter=aMaxMoves
                                & blank=TRUE & pos=zmin
                    THEN    Safe; CheckPosNotOk(zmin); MoveZ(zmin); astate1:=amove1;
                                awaited:=FALSE
                    WHEN    astate1=aidle1 & acmd=move & move_counter=aMaxMoves
                                & blank=FALSE & pos=zmid
                    THEN    Safe; CheckPosNotOk(zmid); MoveZ(zmid); astate1:=amove1;
                                awaited:=FALSE
                    END   END;

        /* waiting for the Robot to be Safe */
    MoveWait=
        SELECT astate1=aidle1 & acmd=move & awaited=FALSE
        THEN awaited:=TRUE  END;

        /* failure - the Robot was not Safe */
    MoveAFail=
        SELECT  astate1=aidle1 & acmd=move & awaited=TRUE
        THEN    NotSafe; astate1:=asuspended1; awaited:=FALSE  END;

        /* protocol failure - the Analyser has moved aMaxMoves times and the next
                    move would not change its position */
    MoveANoPosChangeFail(pos)=
        PRE     pos:NAT
        THEN        SELECT  astate1=aidle1 & acmd=move & move_counter=aMaxMoves
                    THEN    CheckPosOk(pos); astate1:=asuspended1; awaited:=FALSE  END
        END;
```

```
    /* protocol failure - the Analyser  has moved aMaxMoves times. It has a plate
                            that it should deliver, but the given 'pos' is not zmin */
MoveAMinFail(pos)=
    PRE    pos:NAT
    THEN       SELECT  astate1=aidle1 & acmd=move & move_counter=aMaxMoves &
                            pos/=zmin & blank=TRUE
               THEN    astate1:=asuspended1; awaited:=FALSE  END   END;

    /* fix the problem */
MoveAMinRemedy=
    SELECT     astate1=asuspended1 & acmd=move & move_counter=aMaxMoves &
               blank=TRUE & zpos/=zmin
    THEN       Safe; MoveZ(zmin); astate1:=aidle1  END;

    /* protocol failure - the Analyser  has moved aMaxMoves times. It
                            should receive a plate, but the given 'pos' is not zmid */
MoveAMidFail(pos)=
    PRE    pos:NAT
    THEN       SELECT  astate1=aidle1 & acmd=move & move_counter=aMaxMoves &
                            pos/=zmid & blank=FALSE
               THEN    astate1:=asuspended1; awaited:=FALSE  END   END;

    /* fix the problem */
MoveAMidRemedy=
    SELECT     astate1=asuspended1 & acmd=move & move_counter=aMaxMoves &
                    blank=FALSE & zpos/=zmid
    THEN       Safe; MoveZ(zmid); astate1:=aidle1  END;

    /* the given parameter 'pos' is not in range */
MoveARangeFail(pos)=
    PRE    pos:NAT
    THEN       SELECT  astate1=aidle1 & acmd=move
               THEN    NotInRange(pos); astate1:=asuspended1; awaited:=FALSE  END   END;

    /* the Analyser  has reached the position 'pos' */
MoveAReady(pos)=
    PRE    pos:NAT
    THEN       SELECT  astate1=amove1 & acmd=move
               THEN    CheckPosOk(pos); astate1:=aidle1  END   END;

    /* the Analyser  has not reached the position 'pos' */
MoveANotReady(pos)=
    PRE    pos:NAT
    THEN       SELECT  astate1=amove1 & acmd=move
               THEN    CheckPosNotOk(pos); astate1:=amsuspended1  END   END;

    /* fix the problem */
MoveRemedy(pos)=
    PRE  pos:NAT
```

```
        THEN      SELECT  astate1=amsuspended1 & acmd=move
                  THEN    Safe; MoveZ(pos); astate1:=amove1  END  END;

/******************************************************************/
        /* Analyse the plate */
    Analyse=
        SELECT  astate1=aidle1 & acmd=analyse & analyse_counter<aMaxAnalyse
        THEN    PlateInAnalyser; BlankInAnalyser; CheckPosOk(zmax);
                  astate1:=aanalyse1; analyse_counter:=analyse_counter+1  END;

        /* general failure */
    AnalyseFail=
        SELECT astate1=aidle1 & acmd=analyse THEN astate1:=asuspended1  END;

        /* the Analyser  has already analysed the plate aMaxAnalyse times */
    AnalyseMaxFail=
        SELECT    astate1=aidle1 & acmd=analyse & analyse_counter=aMaxAnalyse
        THEN      astate1:=asuspended1  END;

        /* fix the problem */
    AnalyseMaxRemedy=
        SELECT    astate1=asuspended1 & acmd=analyse & analyse_counter=aMaxAnalyse
        THEN      Safe; MoveZ(zmin); astate1:=aidle1  END;

        /* failure - no plate in Analyser */
    AnalysePlateFail=
        SELECT  astate1=aidle1 & acmd=analyse
        THEN    NoPlateInAnalyser; astate1:=asuspended1  END;

        /* failure - the Analyser senses no plate */
    AnalyseBlankFail=
        SELECT  astate1=aidle1 & acmd=analyse
        THEN    NoBlankInAnalyser; astate1:=asuspended1  END;

        /* fix the problem */
    AnalyseBlankRemedy=
        SELECT    astate1=asuspended1 & acmd=analyse & blank=FALSE
        THEN      ChangeBlank(TRUE); astate1:=aidle1  END;

        /* failure - wrong position for analysing */
    AnalysePosFail=
        SELECT  astate1=aidle1 & acmd=analyse
        THEN    CheckPosNotOk(zmax); astate1:=asuspended1  END;

        /* fix the problem */
    AnalysePosRemedy=
        SELECT    astate1=asuspended1 & acmd=analyse & zpos/=zmax
        THEN      Safe; MoveZ(zmax); astate1:=aidle1  END;
```

```
        /* the analysis is done */
    AnalyseReady=
        SELECT  astate1=aanalyse1 & acmd=analyse  THEN  astate1:=aidle1  END;

        /* failure - the analysis has not been done */
    AnalyseNotReady=
        SELECT  astate1=aanalyse1 & acmd=analyse  THEN  astate1:=aasuspended1  END;

        /* fix the problem */
    AnalyseRemedy=
        SELECT  astate1=aasuspended1 & acmd=analyse
        THEN        PlateInAnalyser; BlankInAnalyser; CheckPosOk(zmax);
                        astate1:=aanalyse1  END;

/***************************************************************/
        /* deliver a plate to the Robot */
    Deliver=
        SELECT  astate1=aidle1 & acmd=deliver
        THEN    PlateInAnalyser; BlankInAnalyser; CheckPosOk(zmin); ReadyFor_blank;
                    ChangeBlank(FALSE); astate1:=adeliver1; awaited:=FALSE  END;

        /* general failure */
    DeliverFail=
        SELECT  astate1=aidle1 & acmd=deliver
        THEN    astate1:=asuspended1; awaited:=FALSE  END;

        /* waiting for the Robot to be ready */
    DeliverWait=
        SELECT  astate1=aidle1 & acmd=deliver & awaited=FALSE
        THEN    awaited:=TRUE  END;

        /* failure - no plate to deliver */
    DeliverPlateFail=
        SELECT  astate1=aidle1 & acmd=deliver
        THEN    NoPlateInAnalyser; astate1:=asuspended1; awaited:=FALSE  END;

        /* failure - Analyser senses no plate to deliver */
    DeliverBlankFail=
        SELECT  astate1=aidle1 & acmd=deliver
        THEN    NoBlankInAnalyser; astate1:=asuspended1; awaited:=FALSE  END;

        /* fix the problem */
    DeliverBlankRemedy=
        SELECT    astate1=asuspended1 & acmd=deliver & blank=FALSE
        THEN   ChangeBlank(TRUE); astate1:=aidle1  END;

        /* failure - operating table at wrong position */
    DeliverPosFail=
        SELECT  astate1=aidle1 & acmd=deliver
        THEN    CheckPosNotOk(zmin); astate1:=asuspended1; awaited:=FALSE  END;
```

```
        /* fix the problem */
    DeliverPosRemedy=
        SELECT    astate1=asuspended1 & acmd=deliver & zpos/=zmin
        THEN      Safe; MoveZ(zmin); astate1:=aidle1  END;

        /* failure - the Robot is not ready */
    DeliverFailAtRobot=
        SELECT  astate1=aidle1 & acmd=deliver & awaited=TRUE
        THEN    NotReadyFor_blank; astate1:=asuspended1; awaited:=FALSE  END;

        /* plate delivered ok */
    DeliverReady=
        SELECT  astate1=adeliver1 & acmd=deliver
        THEN    NoPlateInAnalyser; NoBlankInAnalyser; astate1:=aidle1;
                  move_counter:=0; analyse_counter:=0  END;

        /* general 'plate delivery not ok' */
    DeliverNotReady=
        SELECT  astate1=adeliver1 & acmd=deliver  THEN    astate1:=adsuspended1  END;

        /* failure - there is still a plate in the Analyser  */
    DeliverNotReadyPlate=
        SELECT  astate1=adeliver1 & acmd=deliver
        THEN    PlateInAnalyser; astate1:=adsuspended1  END;

        /* failure - the Analyser still senses a plate */
    DeliverNotReadyBlank=
        SELECT  astate1=adeliver1 & acmd=deliver
        THEN    BlankInAnalyser;  astate1:=adsuspended1  END;

        /* fix the problem */
    DeliverRemedy=
        SELECT  astate1=adsuspended1 & acmd=deliver
        THEN    NoPlateInAnalyser; Safe;
                  ChangeBlank(FALSE); MoveZ(zmin); astate1:=adeliver1  END;

/***************************************************************/
        /* receive a plate from the Robot */
    Receive=
        SELECT  astate1=aidle1 & acmd=receive
        THEN    NoPlateInAnalyser; NoBlankInAnalyser; CheckPosOk(zmid);
                Available_blank; ChangeBlank(TRUE); astate1:=areceive1; awaited:=FALSE   END;

        /* general failure */
    ReceiveFail=
        SELECT  astate1=aidle1 & acmd=receive
        THEN    astate1:=asuspended1; awaited:=FALSE  END;
```

```
        /* waiting for the Robot to be ready */
ReceiveWait=
        SELECT  astate1=aidle1 & acmd=receive & awaited=FALSE
        THEN    awaited:=TRUE   END;

        /* failure - there is already a plate in the Analyser  */
ReceivePlateFail=
        SELECT  astate1=aidle1 & acmd=receive
        THEN    PlateInAnalyser; astate1:=asuspended1; awaited:=FALSE  END;

        /* failure - the Analyser  already senses a plate */
ReceiveBlankFail=
        SELECT  astate1=aidle1 & acmd=receive
        THEN    BlankInAnalyser; astate1:=asuspended1; awaited:=FALSE  END;

        /* fix the problem */
ReceiveBlankRemedy=
        SELECT    astate1=asuspended1 & acmd=receive & blank=TRUE
        THEN   ChangeBlank(FALSE); astate1:=aidle1  END;

        /* failure - operating table at wrong position */
ReceivePosFail=
        SELECT  astate1=aidle1 & acmd=receive
        THEN   CheckPosNotOk(zmid); astate1:=asuspended1; awaited:=FALSE  END;

        /* fix the problem */
ReceivePosRemedy=
        SELECT    astate1=asuspended1 & acmd=receive & zpos/=zmid
        THEN   Safe; MoveZ(zmid); astate1:=aidle1  END;

        /* failure - there is no plate available from the Robot */
ReceiveFailAtRobot=
        SELECT  astate1=aidle1 & acmd=receive & awaited=TRUE
        THEN    NoAvailable_blank; astate1:=asuspended1; awaited:=FALSE  END;

        /* plate received ok */
ReceiveReady=
        SELECT  astate1=areceive1 & acmd=receive
        THEN    PlateInAnalyser; BlankInAnalyser; astate1:=aidle1; move_counter:=0   END;

        /* plate not received properly */
ReceiveNotReady=
        SELECT  astate1=areceive1 & acmd=receive  THEN    astate1:=arsuspended1  END;

        /* failure - the Analyser  has not got a plate */
ReceiveNotReadyPlate=
        SELECT  astate1=areceive1 & acmd=receive
        THEN    NoPlateInAnalyser; astate1:=arsuspended1   END;
```

```
        /* failure - the Analyser  does not sense a blank */
    ReceiveNotReadyBlank=
        SELECT  astate1=areceive1 & acmd=receive
        THEN    NoBlankInAnalyser; astate1:=arsuspended1  END;

        /* fix the problem */
    ReceiveRemedy=
        SELECT  astate1=arsuspended1 & acmd=receive
        THEN    PlateInAnalyser; Safe; ChangeBlank(TRUE); MoveZ(zmid); astate1:=areceive1   END;

/******************************************************************************/
        /* general 'not ready' failure */
    AServiceNotReady=    SELECT  astate1=aidle1 THEN astate1:=asuspended1 END;

        /* fix the problem */
    ARemedy=        SELECT    astate1=asuspended1 THEN astate1:=aidle1 END;

        /* there is no remedy for the problem */
    AFailure=   SELECT  astate1:{asuspended1, amsuspended1, aasuspended1,
                                                  arsuspended1, adsuspended1}
            THEN    astate1:=aabort1   END
END
```

C.2 The sets of the refined Analyser def1.mch

In *def1.mch* we define the sets of states and commands used in the Analyser. The three possible positions of the operating table, as well as the maximum number of moves and analyses are given as constants.

```
MACHINE
    def1
SETS
    ASTATE={aidle, amove, aanalyse, areceive, adeliver, asuspended, aabort};
    ASTATE1={aidle1, amove1, aanalyse1, areceive1, adeliver1, asuspended1, amsuspended1,
                    aasuspended1, arsuspended1, adsuspended1, aabort1};
    ACOMMAND={move, analyse, deliver, receive}
CONSTANTS
    zmax, zmin, zmid, aMaxMoves, aMaxAnalyse
PROPERTIES
    zmax:NAT  &  zmin:NAT  &  zmid:NAT &
    zmax>zmin  &  zmax>zmid  &  zmin<zmid  &
    aMaxMoves:NAT  &  aMaxAnalyse:NAT
END
```

C.3 The procedures A_proc1.mch

The refined global procedures of the Analyser are given in *A_proc1.ref*. Also the local variables of the Analyser are given in this machine.

```
MACHINE
      A_proc1
SEES
      def1
VARIABLES
      zpos, blank
INVARIANT
      zpos:NAT  &  zpos:zmin..zmax  &
         blank:BOOL
INITIALISATION
      zpos:=zmid || blank:=FALSE
OPERATIONS
                  /* Global procedures */

            /* the Analyser is ready to deliver a plate */
      ReadyToDeliver=        SELECT  zpos=zmin & blank=TRUE  THEN  skip  END;

            /* the Analyser  is not ready to deliver a plate */
      NotReadyToDeliver=   SELECT  zpos/=zmin or blank=FALSE  THEN  skip  END;

            /* the Analyser  is ready to receive a plate */
      ReadyToReceive=      SELECT  zpos=zmid & blank=FALSE  THEN  skip  END;


            /* the Analyser  is not ready to receive a plate */
      NotReadyToReceive= SELECT  zpos/=zmid or blank=TRUE  THEN  skip  END;

            /* the Analyser  senses a plate */
      BlankInAnalyser=       SELECT  blank=TRUE  THEN  skip  END;

            /* the Analyser  does not sense a plate */
      NoBlankInAnalyser=   SELECT  blank=FALSE  THEN  skip  END;

/****************************************************************/
                  /* Local procedures */

            /* change the sensor 'blank' */
      ChangeBlank(bb)=      PRE  bb:BOOL  THEN  blank:=bb  END;

            /* move the operating table to 'pos' */
      MoveZ(pos)=
            PRE  pos:NAT  THEN   SELECT  pos:zmin..zmax  THEN  zpos:=pos  END  END;
```

```
        /* check if 'pos' is in range */
    InRange(pos)=
        PRE  pos:NAT  THEN   SELECT  pos<=zmax & pos>=zmin  THEN  skip  END  END;

        /* check if 'pos' is not in range */
    NotInRange(pos)=
        PRE  pos:NAT  THEN  SELECT  pos<zmin or pos>zmax  THEN  skip  END   END;

        /* check if the operating table is at 'pos' */
    CheckPosOk(pos)=
        PRE  pos:NAT  THEN  SELECT  pos=zpos  THEN  skip  END   END;

        /* check if the operating table is not at 'pos' */
    CheckPosNotOk(pos)=
        PRE  pos:NAT  THEN  SELECT  pos/=zpos  THEN  skip  END   END
END
```

Appendix D: The second refinement step of the Analyser

D.1 The final refined Analyser Analyser2.ref

The further refined Analyser is given as the machine refinement *Analyser2.ref*. The liquid amounts *pl_liq, pl_liq_tmp* are the newly introduced variables in this refinement step. The temporal variable *pl_liq_tmp* is declared in *Analyser2.ref* and states the amount of liquid on the plate in the beginning of the current analysis.

```
REFINEMENT
      Analyser2
REFINES
      Analyser1
SEES
      def1
INCLUDES
      R_proc, A_proc2, GlobalVar_Plate
VARIABLES
      astate1, acmd, awaited, move_counter, analyse_counter, pl_liq_tmp
INVARIANT
      pl_liq_tmp:NAT &
      (blank=FALSE => pl_liq=0)
INITIALISATION
      astate1:=aidle1 || acmd:=receive || awaited:=FALSE ||
      move_counter,analyse_counter:=0,0 ||  pl_liq_tmp:=0

OPERATIONS
      NewCommand(cc)=
            PRE    cc:ACOMMAND
            THEN   SELECT   astate1=aidle1 & awaited=FALSE  THEN  acmd:=cc  END
            END;

/*****************************************************************/
            /* move to position 'pos' */
      MoveA(pos)=
            PRE    pos:NAT
            THEN       SELECT  astate1=aidle1 & acmd=move & move_counter<aMaxMoves
                       THEN       Safe; InRange(pos); MoveZ(pos); astate1:=amove1;
                                  awaited:=FALSE; move_counter:=move_counter+1
                       WHEN       astate1=aidle1 & acmd=move & move_counter=aMaxMoves
                                  & blank=TRUE & pos=zmin
                       THEN       Safe; CheckPosNotOk(zmin); MoveZ(zmin); astate1:=amove1;
                                  awaited:=FALSE
                       WHEN       astate1=aidle1 & acmd=move & move_counter=aMaxMoves
                                  & blank=FALSE & pos=zmid
```

```
                THEN      Safe; CheckPosNotOk(zmid); MoveZ(zmid); astate1:=amove1;
                          awaited:=FALSE
            END   END;

        /* waiting for the Robot to be Safe */
MoveWait=
        SELECT  astate1=aidle1 & acmd=move & awaited=FALSE
        THEN  awaited:=TRUE END;

        /* failure - the Robot was not Safe */
MoveAFail=
        SELECT  astate1=aidle1 & acmd=move & awaited=TRUE
        THEN    NotSafe; astate1:=asuspended1; awaited:=FALSE  END;

        /* protocol failure - the Analyser has moved aMaxMoves times and the next
                          move would not change its position */
MoveANoPosChangeFail(pos)=
        PRE     pos:NAT
        THEN        SELECT  astate1=aidle1 & acmd=move & move_counter=aMaxMoves
                THEN    CheckPosOk(pos); astate1:=asuspended1; awaited:=FALSE
                END  END;

        /* protocol failure - the Analyser  has moved aMaxMoves times. It has a plate
                          that it should deliver, but the given 'pos' is not zmin */
MoveAMinFail(pos)=
        PRE     pos:NAT
        THEN        SELECT  astate1=aidle1 & acmd=move & move_counter=aMaxMoves &
                          pos/=zmin & blank=TRUE
                THEN    astate1:=asuspended1; awaited:=FALSE  END   END;

        /* fix the problem */
MoveAMinRemedy=
        SELECT    astate1=asuspended1 & acmd=move & move_counter=aMaxMoves &
                blank=TRUE & zpos/=zmin
        THEN   Safe; MoveZ(zmin); astate1:=aidle1  END;

        /* protocol failure - the Analyser  has moved aMaxMoves times. It
                      should receive a plate, but the given 'pos' is not zmid */
MoveAMidFail(pos)=
        PRE     pos:NAT
        THEN        SELECT  astate1=aidle1 & acmd=move & move_counter=aMaxMoves &
                          pos/=zmid & blank=FALSE
                THEN    astate1:=asuspended1; awaited:=FALSE  END   END;

        /* fix the problem */
MoveAMidRemedy=
        SELECT    astate1=asuspended1 & acmd=move & move_counter=aMaxMoves &
                blank=FALSE & zpos/=zmid
        THEN   Safe; MoveZ(zmid); astate1:=aidle1  END;
```

```
        /* the given parameter 'pos' is not in range */
    MoveARangeFail(pos)=
        PRE    pos:NAT
        THEN       SELECT  astate1=aidle1 & acmd=move
                   THEN    NotInRange(pos); astate1:=asuspended1; awaited:=FALSE  END   END;

        /* the Analyser  has reached the position 'pos' */
    MoveAReady(pos)=
        PRE    pos:NAT
        THEN       SELECT  astate1=amove1 & acmd=move
                   THEN    CheckPosOk(pos); astate1:=aidle1  END   END;

        /* the Analyser  has not reached the position 'pos' */
    MoveANotReady(pos)=
        PRE    pos:NAT
        THEN       SELECT  astate1=amove1 & acmd=move
                   THEN    CheckPosNotOk(pos); astate1:=amsuspended1  END   END;

        /* fix the problem */
    MoveRemedy(pos)=
        PRE  pos:NAT
        THEN       SELECT  astate1=amsuspended1 & acmd=move
                   THEN    Safe; MoveZ(pos); astate1:=amove1  END   END;

/*****************************************************************/
        /* Analyse the plate */
    Analyse=
        SELECT  astate1=aidle1 & acmd=analyse & analyse_counter<aMaxAnalyse
        THEN   PlateInAnalyser; BlankInAnalyser; CheckPosOk(zmax);
                   CheckLiqAmt; pl_liq_tmp := pl_liq; AnalysePlate;
                   astate1:=aanalyse1; analyse_counter:=analyse_counter+1  END;

        /* general failure */
    AnalyseFail=
        SELECT astate1=aidle1 & acmd=analyse THEN astate1:=asuspended1  END;

        /* the Analyser  has already analysed the plate aMaxAnalyse times */
    AnalyseMaxFail=
        SELECT    astate1=aidle1 & acmd=analyse & analyse_counter=aMaxAnalyse
        THEN      astate1:=asuspended1  END;

        /* fix the problem */
    AnalyseMaxRemedy=
        SELECT    astate1=asuspended1 & acmd=analyse & analyse_counter=aMaxAnalyse
        THEN      Safe; MoveZ(zmin); astate1:=aidle1  END;

        /* failure - no plate in Analyser */
    AnalysePlateFail=
        SELECT  astate1=aidle1 & acmd=analyse
        THEN    NoPlateInAnalyser; astate1:=asuspended1  END;
```

```
        /* failure - the Analyser  senses no plate */
    AnalyseBlankFail=
        SELECT  astate1=aidle1 & acmd=analyse
        THEN    NoBlankInAnalyser; astate1:=asuspended1  END;

        /* fix the problem */
    AnalyseBlankRemedy=
        SELECT    astate1=asuspended1 & acmd=analyse & blank=FALSE
        THEN      ChangeBlank(TRUE); astate1:=aidle1  END;

        /* failure - wrong position for analysing */
    AnalysePosFail=
        SELECT  astate1=aidle1 & acmd=analyse
        THEN    CheckPosNotOk(zmax); astate1:=asuspended1  END;

        /* fix the problem */
    AnalysePosRemedy=
        SELECT    astate1=asuspended1 & acmd=analyse & zpos/=zmax
        THEN      Safe; MoveZ(zmax); astate1:=aidle1  END;

    AnalyseLiqFail=
        SELECT    astate1=aidle1 & acmd=analyse
        THEN      CheckLiqAmtNotOk; astate1:=asuspended1  END;

        /* the analysis is done */
    AnalyseReady=
        SELECT  astate1=aanalyse1 & acmd=analyse
        THEN    AnalyseOk(pl_liq_tmp); astate1:=aidle1  END;

        /* failure - the analysis has not been done */
    AnalyseNotReady=
        SELECT  astate1=aanalyse1 & acmd=analyse  THEN  astate1:=aasuspended1  END;

    AnalyseNotOkReady=
        SELECT    astate1=aanalyse1 & acmd=analyse
        THEN      AnalyseNotOk(pl_liq_tmp); astate1:=aasuspended1  END;

        /* fix the problem */
    AnalyseRemedy=
        SELECT  astate1=aasuspended1 & acmd=analyse
        THEN    PlateInAnalyser; BlankInAnalyser; CheckPosOk(zmax);  astate1:=aanalyse1  END;

/*************************************************************/
        /* deliver a plate to the Robot */
    Deliver=
        SELECT  astate1=aidle1 & acmd=deliver
        THEN    PlateInAnalyser; BlankInAnalyser; CheckPosOk(zmin); ReadyFor_blank;
                  ChangeBlank(FALSE); ResetPlateLiq; astate1:=adeliver1; awaited:=FALSE  END;
```

```
        /* general failure */
DeliverFail=
        SELECT  astate1=aidle1 & acmd=deliver
        THEN    astate1:=asuspended1; awaited:=FALSE  END;

        /* waiting for the Robot to be ready */
DeliverWait=
        SELECT  astate1=aidle1 & acmd=deliver & awaited=FALSE
        THEN    awaited:=TRUE  END;

        /* failure - no plate to deliver */
DeliverPlateFail=
        SELECT  astate1=aidle1 & acmd=deliver
        THEN    NoPlateInAnalyser; astate1:=asuspended1; awaited:=FALSE  END;

        /* failure - Analyser  senses no plate to deliver */
DeliverBlankFail=
        SELECT  astate1=aidle1 & acmd=deliver
        THEN    NoBlankInAnalyser; astate1:=asuspended1; awaited:=FALSE  END;

        /* fix the problem */
DeliverBlankRemedy=
        SELECT    astate1=asuspended1 & acmd=deliver & blank=FALSE
        THEN      ChangeBlank(TRUE); astate1:=aidle1  END;

        /* failure - operating table at wrong position */
DeliverPosFail=
        SELECT  astate1=aidle1 & acmd=deliver
        THEN    CheckPosNotOk(zmin); astate1:=asuspended1; awaited:=FALSE  END;

        /* fix the problem */
DeliverPosRemedy=
        SELECT    astate1=asuspended1 & acmd=deliver & zpos/=zmin
        THEN      Safe;MoveZ(zmin); astate1:=aidle1  END;

        /* failure - the Robot is not ready */
DeliverFailAtRobot=
        SELECT  astate1=aidle1 & acmd=deliver & awaited=TRUE
        THEN    NotReadyFor_blank; astate1:=asuspended1; awaited:=FALSE  END;

        /* plate delivered ok */
DeliverReady=
        SELECT  astate1=adeliver1 & acmd=deliver
        THEN    NoPlateInAnalyser; NoBlankInAnalyser;
                  astate1:=aidle1; move_counter:=0; analyse_counter:=0  END;

        /* general 'plate delivery not ok' */
DeliverNotReady=
        SELECT  astate1=adeliver1 & acmd=deliver  THEN  astate1:=adsuspended1  END;
```

```
        /* failure - there is still a plate in the Analyser  */
    DeliverNotReadyPlate=
        SELECT  astate1=adeliver1 & acmd=deliver
        THEN   PlateInAnalyser; astate1:=adsuspended1  END;

        /* failure - the Analyser  still senses a plate */
    DeliverNotReadyBlank=
        SELECT  astate1=adeliver1 & acmd=deliver
        THEN   BlankInAnalyser; astate1:=adsuspended1  END;

        /* fix the problem */
    DeliverRemedy=
        SELECT  astate1=adsuspended1 & acmd=deliver & pl_liq = 0
        THEN   NoPlateInAnalyser; Safe;
                ChangeBlank(FALSE); MoveZ(zmin); astate1:=adeliver1   END;

/***************************************************************/
        /* receive a plate from the Robot */
    Receive=
        SELECT  astate1=aidle1 & acmd=receive
        THEN   NoPlateInAnalyser; NoBlankInAnalyser; CheckPosOk(zmid);
                Available_blank; ChangeBlank(TRUE); PlateLiquidRead;
                astate1:=areceive1; awaited:=FALSE   END;

        /* general failure */
    ReceiveFail=
        SELECT  astate1=aidle1 & acmd=receive
        THEN    astate1:=asuspended1; awaited:=FALSE   END;

        /* waiting for the Robot to be ready */
    ReceiveWait=
        SELECT  astate1=aidle1 & acmd=receive & awaited=FALSE
        THEN    awaited:=TRUE   END;

        /* failure - there is already a plate in the Analyser  */
    ReceivePlateFail=
        SELECT  astate1=aidle1 & acmd=receive
        THEN    PlateInAnalyser; astate1:=asuspended1; awaited:=FALSE   END;

        /* failure - the Analyser  already senses a plate */
    ReceiveBlankFail=
        SELECT  astate1=aidle1 & acmd=receive
        THEN    BlankInAnalyser; astate1:=asuspended1; awaited:=FALSE   END;

        /* fix the problem */
    ReceiveBlankRemedy=
        SELECT    astate1=asuspended1 & acmd=receive & blank=TRUE & pl_liq = 0
        THEN   ChangeBlank(FALSE); astate1:=aidle1   END;
```

```
        /* failure - operating table at wrong position */
    ReceivePosFail=
        SELECT  astate1=aidle1 & acmd=receive
        THEN    CheckPosNotOk(zmid); astate1:=asuspended1; awaited:=FALSE   END;

        /* fix the problem */
    ReceivePosRemedy=
        SELECT    astate1=asuspended1 & acmd=receive & zpos/=zmid
        THEN        Safe; MoveZ(zmid); astate1:=aidle1   END;

        /* failure - there is no plate available from the Robot */
    ReceiveFailAtRobot=
        SELECT  astate1=aidle1 & acmd=receive & awaited=TRUE
        THEN    NoAvailable_blank; astate1:=asuspended1; awaited:=FALSE   END;

        /* plate received ok */
    ReceiveReady=
        SELECT  astate1=areceive1 & acmd=receive
        THEN    PlateInAnalyser; BlankInAnalyser; astate1:=aidle1; move_counter:=0   END;

        /* plate not received properly */
    ReceiveNotReady=
        SELECT  astate1=areceive1 & acmd=receive  THEN  astate1:=arsuspended1  END;

        /* failure - the Analyser  has not got a plate */
    ReceiveNotReadyPlate=
        SELECT  astate1=areceive1 & acmd=receive
        THEN    NoPlateInAnalyser; astate1:=arsuspended1   END;

        /* failure - the Analyser  does not sense a blank */
    ReceiveNotReadyBlank=
        SELECT  astate1=areceive1 & acmd=receive
        THEN    NoBlankInAnalyser; astate1:=arsuspended1   END;

        /* fix the problem */
    ReceiveRemedy=
        SELECT  astate1=arsuspended1 & acmd=receive
        THEN   PlateInAnalyser; Safe;
                    ChangeBlank(TRUE); MoveZ(zmid); astate1:=areceive1   END;

/*******************************************************************************/
        /* general 'not ready' failure */
    AServiceNotReady=    SELECT  astate1=aidle1 THEN astate1:=asuspended1 END;

        /* fix the problem */
    ARemedy= SELECT  astate1=asuspended1 THEN astate1:=aidle1 END;
```

```
        /* there is no remedy for the problem */
    AFailure=   SELECT  astate1:{asuspended1, amsuspended1, aasuspended1,
                                                    arsuspended1, adsuspended1}
                THEN  astate1:=aabort1   END
END
```

D.2 The procedures A_proc2.mch

The exported procedures that will be called by the Robot as well as the local procedures of the refined Analyser *Analyser2* are given in machine *A_proc2.mch*. The new variable *pl_liq* give the amount of liquid in the current plate.

```
MACHINE
    A_proc2
SEES
    def1, Liq_def
VARIABLES
    zpos, blank, pl_liq
INVARIANT
    zpos:NAT  &  zpos:zmin..zmax  &  blank:BOOL & pl_liq:NAT
INITIALISATION
    zpos:=zmid  ||  blank:=FALSE || pl_liq:=0
OPERATIONS
                /* Global procedures */

        /* the Analyser is ready to deliver a plate */
    ReadyToDeliver=        SELECT    zpos=zmin & blank=TRUE  THEN  skip  END;

        /* the Analyser is not ready to deliver a plate */
    NotReadyToDeliver=   SELECT    zpos/=zmin or blank=FALSE  THEN  skip  END;

        /* the Analyser is ready to receive a plate */
    ReadyToReceive=       SELECT    zpos=zmid & blank=FALSE THEN  skip  END;

        /* the Analyser is not ready to receive a plate */
    NotReadyToReceive= SELECT    zpos/=zmid or blank=TRUE THEN  skip  END;

        /* the Analyser senses a plate */
    BlankInAnalyser=        SELECT    blank=TRUE THEN skip END;

        /* the Analyser does not sense a plate */
    NoBlankInAnalyser=    SELECT    blank=FALSE THEN skip END;
```

```
/***************************************************************/
                    /* Local procedures */

          /* change the sensor 'blank' */
     ChangeBlank(bb)=      PRE  bb:BOOL  THEN  blank:=bb  END;

          /* move the operating table to 'pos' */
     MoveZ(pos)=
          PRE  pos:NAT & pos:zmin..zmax   THEN zpos:=pos  END;

          /* check if 'pos' is in range */
     InRange(pos)=
          PRE  pos:NAT  THEN   SELECT  pos<=zmax  & pos>=zmin  THEN  skip  END  END;

          /* check if 'pos' is not in range */
     NotInRange(pos)=
          PRE  pos:NAT   THEN   SELECT  pos<zmin or pos>zmax THEN skip END   END;

          /* check if the operating table is at 'pos' */
     CheckPosOk(pos)=
          PRE   pos:NAT  THEN   SELECT  pos=zpos  THEN  skip  END   END;

          /* check if the operating table is not at 'pos' */
     CheckPosNotOk(pos)=
          PRE  pos:NAT  THEN   SELECT  pos/=zpos  THEN  skip  END   END;

          /* read the liquid level of the plate */
     PlateLiquidRead=      BEGIN      pl_liq::(0..pmax)  END;

          /* reset the liquid level to zero */
     ResetPlateLiq=        BEGIN      pl_liq:=0    END;

          /*  check if there is enough liquid, anl_liq, for analysing */
     CheckLiqAmt=          SELECT anl_liq<=pl_liq   THEN  skip  END;

          /*  check if there is not enough liquid, anl_liq, for analysing */
     CheckLiqAmtNotOk=   SELECT  pl_liq<anl_liq  THEN  skip  END;

          /*  take an amount of liquid, anl_liq, for analysing from the plate */
     AnalysePlate=         PRE  pl_liq-anl_liq:0..pmax  THEN  pl_liq:=pl_liq-anl_liq  END;

          /* check if the right amount of liquid, anl_liq, was used for the analysis */
     AnalyseOk(aa)=
          PRE  aa:NAT  THEN   SELECT  pl_liq+anl_liq=aa  THEN  skip  END   END;

          /* check if an incorrect amount of liquid, anl_liq, was used for the analysis */
     AnalyseNotOk(aa)=
          PRE  aa:NAT  THEN   SELECT  pl_liq+anl_liq/=aa  THEN  skip  END   END
END
```

D.3 The constants of the final refined Analyser Liq_def.mch

In *Liq_def.mch* we define the constants concerning the liquid used in *Analyser2*. The constant *anl_liq* states the amount of liquid needed for each analysis and *pmax* is the maximum capacity of each plate.

```
MACHINE
        Liq_def
CONSTANTS
        anl_liq, pmax
PROPERTIES
        anl_liq:NAT  &  pmax:NAT  &  anl_liq:0..pmax
END
```

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