Compositional Design of Multi-Agent Systems: Modelling Dynamics and Control

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Compositional Design of Multi-Agent Systems: Modelling Dynamics and Control

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1 Introduction

The compositional multi-agent development method DESIRE (DEsign and Specification of Interacting REasoning components) supports the design of autonomous interactive agents. Both the *intra-agent functionality* (i.e., the expertise required to perform the tasks for which an agent is responsible in terms of the knowledge, and reasoning and acting capabilities) and the *inter-agent functionality* (i.e., the expertise required to perform and guide co-ordination, co-operation and other forms of social interaction in terms of knowledge, and reasoning and acting capablities) are explicitly modelled. DESIRE views both the individual agents and the overall system as compositional structures - hence all functionality is designed in terms of interacting, compositionally structured components. Complex distributed processes are the result of tasks performed by agents in interaction with their environment. In this paper in particular it is discused how dynamics and the control of dynamics of reasoning processes are modelled using this compositional approach. Examples are discussed of reasoning patterns in which assumptions are dynamically introduced, evaluated and, if needed, retracted (temporal epistemic reflection), and reasoning patterns in which the reasoning process is focussed by dynamic generation of goals for the reasoning.

1.1 The design process

The design of a multi-agent system is an iterative process, which aims at the identification of the parties involved (i.e., human agents, system agents, external worlds), and the processes, in addition to the types of knowledge needed. Conceptual descriptions of specific processes and knowledge are often first attained. Further explication of these conceptual design descriptions results in detailed design descriptions, most often in iteration with conceptual design. During the design of these models, partial prototype implementations may be used to analyse or verify the resulting behaviour. On the basis of examination of these partial prototypes, new designs and prototypes are generated and examined, and so on and so forth. This approach to *evolutionary development* of systems, is characteristic to the development of multi-agent systems in DESIRE.

During a multi-agent system development process, DESIRE distinguishes the following descriptions (see Figure 1):

- problem description
- conceptual design
- detailed design
- operational design
- design rationale

The *problem description* includes the *requirements* imposed on the design. The *rationale* specifies the choices made during design at each of the levels, and assumptions with respect to its use.

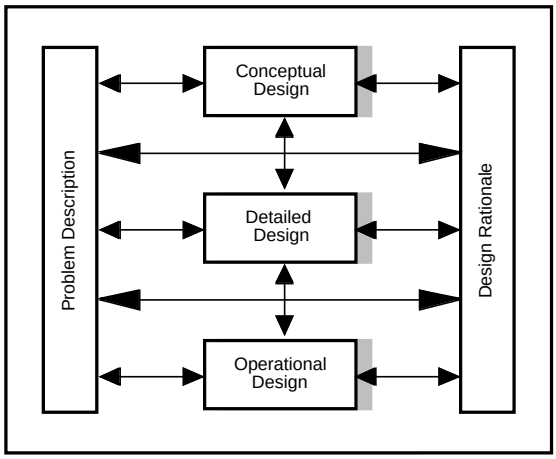


Figure 1 Problem description, levels of design and design rationale

The relationship between the levels of design (conceptual, detailed, operational) is well-defined and structure-preserving. The *conceptual design* includes conceptual models for each individual agent, the external world and the interaction between agents, and between agents and the external world. The *detailed design* of a system, based on the conceptual design, specifies all aspects of a system's knowledge and behaviour. A detailed design is an adequate basis for *operational design*. Prototype implementations, are automatically generated from the detailed design.

There is no fixed sequence of design: depending on the specific situation, different types of knowledge are available at different points during system design. The end result, the final multi-agent system design, is specified by the system designer at the level of detailed design. In addition, important assumptions and design decisions are specified in the design rationale. Alternative design options together with argumentation are included. On the basis of verification during the design process, properties of models can be documented with the related assumptions. The assumptions define the limiting conditions under which the model will exhibit specific behaviour.

1.2 Compositionality of processes and knowledge

Compositionality is a general principle that refers to the use of components to structure a design. Within the DESIRE method components are often complex compositional structures in which a number of other, more specific components are grouped. During design different levels of process abstraction are identified. Processes at each of these levels (except the lowest level) are modelled as (process) *components* composed of components at the adjacent lower level.

Processes within a multi-agent system may be viewed as the result of interaction between more specific processes. A complete multi-agent system may, for example, be seen to be one single component responsible for the performance of the overall process. Within this one single component a number of agent components and an external world can be distinguished, each responsible for a more specific process. Each agent component may, in turn, have a number of internal components responsible for more specific parts of this process. These components may themselves be composed, again entailing interaction between other more specific processes.

The *ontology* used to express the knowledge needed to reason about a specific domain may also be seen as a single (knowledge) component. This *knowledge structure* can be composed of a number of more specific knowledge structures which, in turn, may again be composed of other even more specific knowledge structures.

As shown in Figure 2 *compositionality of processes* and *compositionality of knowledge* are two separate, orthogonal dimensions. The compositional knowledge structures are referenced by compositional process structures, when needed.

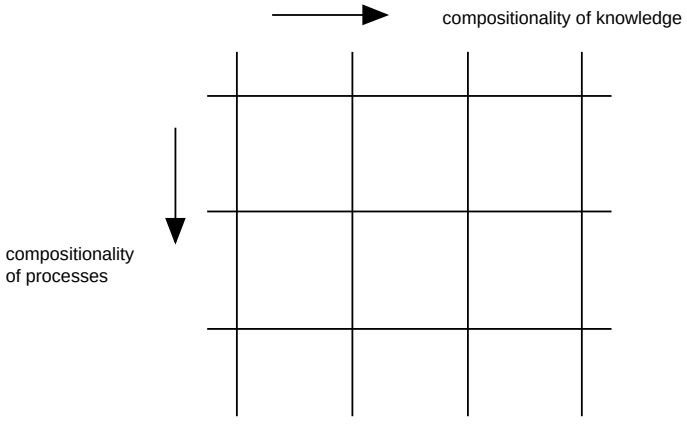


Figure 2 Compositionality of processes and compositionality of knowledge

Compositionality is a means to acquire *information and process hiding* within a model: by defining processes and knowledge at different levels of abstraction, unnecessary detail can be hidden. Compositionality also makes it possible to *integrate* different types of components in one agent. Components and groups of components can be easily included in new designs, supporting *reuse* of components at all levels of design.

2 Problem description

Which techniques are used to acquire a *problem description* is not pre-defined. Techniques vary in their applicability, depending on, for example, the situation, the task, the type of knowledge on which the system developer wishes to focus. Acquisition of requirements to be imposed on the system as part of the problem description is crucial. These requirements are part of the initial problem definition, but may also evolve during the development of a system. To illustrate the concepts introduced in this chapter an example is used of an information gathering and analysis task: diagnosis of refridgerator problems.

To make decisions, often agents have to analyse a given situation by gathering information and drawing conclusions from the gathered information. Gathering (the right type of) information requires effort. To use an agent's resources economically, an information gathering process should concentrate on gathering only information that is relevant for the conclusions the agent wants to be able to draw. Ideally, an agent can focus an information gathering process by strategic reasoning. Such a reasoning process is, for example, necessary in situations in which unexpected behaviour occurs in the environment, and the cause of this deviant behaviour has to be analysed (this process is sometimes called *diagnosis*). In this section an example of a strategic reasoning process to guide information gathering is discussed. The conclusions in which the agent is interested are called *hypotheses*. Information gathering is assumed to take place by *observation* (for information gathering based on, for example, communication, the pattern is similar).

Viewed from a global perspective, the agent performs a coherent and well-structured pattern of reasoning which subsequently (and iteratively) involves determining one or more hypotheses on which to focus, and confirming or rejecting these hypotheses on the basis of observations:

- determine the hypotheses on which to focus (*focus hypotheses*)
- validate these focus hypotheses:
    - determine relevant observations on which to focus (*focus observations*)
    - perform these focus observations
    - evaluate the focus hypotheses on the basis of the observation results
    - repeat this (hypothesis validation) process
- repeat the whole process

The example diagnostic process used in this chapter is a simplified case of diagnosis of refrigerator malfunctioning. Four types of faults are considered:

- the light *bulb* is *broken*,
- there is *no power supply*,
- the *pump* is *broken*, and
- the *cooling system* is *broken*.

Only three observations can be performed:

- if the door is opened there is (no) *light*,
- (no) *noise* of the pump is heard, and
- it is (not) *cold* in the fridge.

Assumptions are:

- only situations in which one type of fault occurs are considered (*single fault assumption*)

Requirements are:

- for each situation a correct diagnosis shall be determined
- the diagnostic process shall be parsimonous: the most efficient effort of observation shall be performed during the diagnostic process to reach a conclusion

3 Conceptual design and detailed design

A conceptual and detailed design consist of specifications of the following three types:

- process composition,
- knowledge composition,
- the relation between process composition and knowledge composition.

These three types of specifications are discussed in more detail below.

3.1 Process composition

Process composition identifies the relevant processes at different levels of (process) abstraction, and describes how a process can be defined in terms of lower level processes.

3.1.1 Identification of processes at different levels of abstraction

Different views can be taken: a task perspective, and a multi-agent perspective. The *task perspective* refers to the view in which the processes needed to perform an overall task are distinguished. These processes (or sub-tasks) are then *delegated* to appropriate agents and the external world. The *multi-agent perspective* refers to the view in which agents and one or more external worlds are first distinguished and then the processes within them, including agent-related processes such as management of communication, or control of an agent's own processes.

Specification of a process
The identified processes are modelled as *components*. For each process the *types of information* used as input and resulting as output are identified as well, and modelled as *input and output interfaces* of the component.

To model the example refridgerator diagnosis process, a generic task model for diagnosis can be used consisting at the top level of a reasoning process and an external world in which observation results are obtained. The reasoning process is composed of the processes hypothesis determination and hypothesis validation, where the hypothesis validation process is composed of the processes observation determination and hypothesis evaluation. Based on this generic model the following processes are identified for the example diagnostic process: external world, and diagnostic reasoning, with sub-processes hypothesis determination and hypothesis validation. The process hypothesis validation has two sub-processes: observation determination and hypothesis evaluation. The types of information used and produced by each of these tasks are shown in Figures 1, 2 and 3.

process	*input information type*	*output information type*
Diagnostic Reasoning	Observation Result Info	Assessed Hypotheses Selected Observations
External World	Required Observations	Observation Result Info

Figure 3 Interface information types within the Top Level

As shown in Figure 3 three information types are distinguised for the process as a whole. The diagnostic reasoning process generates information on specific (focus) observations that are selected (Selected Observations), and assessments of hypotheses (Assessed Hypothese). It requires observation results (Observation Result Info) as input. Acquisition of information in the external world, is focussed on the basis of information on the observations to be performed (Required Observations) and provides the results (Observation Result Info).

Figure 4 depicts the input and output information types of the processes within the diagnostic reasoning process. The process of determining on which hypotheses to focus, Hypothesis Determination, uses information on which hypotheses have already been assessed (Assessed Hypotheses), which hypotheses have already been in focus (Selected Hypotheses) and results of observations that have been performed. The result is a list of one or more hypotheses which may be used to focus the diagnostic process (Selected Hypotheses).

process	*input information type*	*output information type*

Hypothesis Determination	Assessed Hypotheses Selected Hypotheses	Selected Hypotheses
Hypothesis Validation	Observation Result Info Focussed Hypotheses	Assessed Hypotheses Selected Observations

Figure 4 Interface information types within Diagnostic Reasoning

The process of validating one or more hypotheses, Hypothesis Validation, uses information on the hypotheses on which to focus (Focussed Hypotheses) and results of observations (Observation Result Info). During validation, often a need for specific information is identified (Selected Observations). Once the validation process has been completed the results - hypotheses that have been assessed (Assessed Hypotheses) - are available as output.

process	*input information type*	*output information type*
Observation Determination	Focussed Hypotheses Observation Information	Selected Observations
Hypothesis Evaluation	Target Domain Hypotheses Assumption Domain Info Domain Info	Epistemic Domain Hypotheses Epistemic Domain Info Domain Info Domain Hypotheses

Figure 5 Interface information types within Hypothesis Validation

Figure 5 depicts the information types used and produced by the processes needed to validate hypotheses. To determine which observations to perform, Observation Determination, information is needed on the hypotheses on which to focus (Focussed Hypotheses) and the available information on observations (Observation Information). The results of this process are a list of one or more observations to be performed (Selected Observations). The process Hypothesis Evaluation, involves evaluating one or more hypotheses (Target Domain Hypotheses) on the basis of information on observations performed (Assumption Domain Info). The result is an evaluation of the hypotheses (Epistemic Domain Hypotheses) on which evaluation focussed.

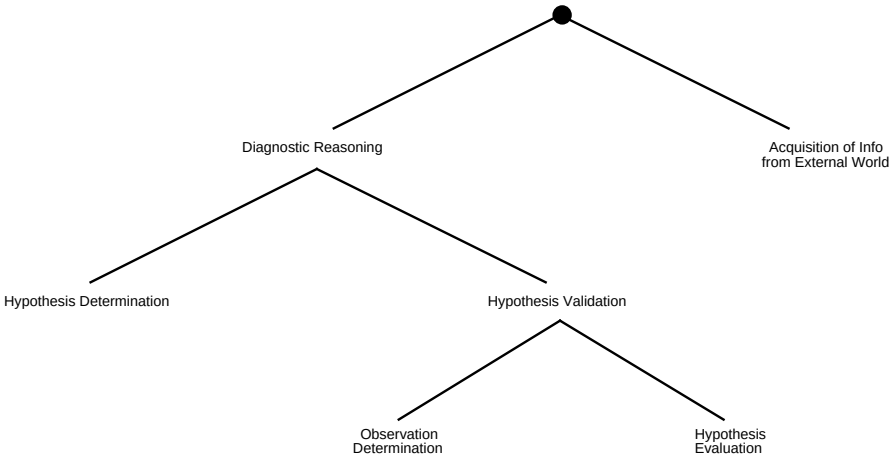


Figure 6 Process abstraction levels in a strategic information gathering process

Specification of abstraction levels

The identified levels of process abstraction are modelled as *abstraction/specialisation relations* between components at adjacent levels of abstraction: components may be *composed* of other components or they may be *primitive*. Primitive components may be either reasoning components (for example based on a knowledge base), or, alternatively, components capable of performing tasks such as calculation, information retrieval, optimisation, et cetera.

For the example diagnostic reasoning process the process abstraction levels are depicted in Figure 6. The identification of processes at different abstraction levels results in specification of components that can be used as building blocks, and of a specification of the sub-component relation, defining which components are a sub-component of a which other component. The distinction of different process abstraction levels results in process hiding.

3.1.2 Composition

The way in which processes at one level of abstraction are composed of processes at the adjacent lower abstraction level is called *composition*. This composition of processes is described by the possibilities for *information exchange* between processes (*static view* on the composition), and *task control knowledge* used to control processes and information exchange (*dynamic view* on the composition).

Information exchange

A specification of information exchange defines which types of information can be transferred between components and the *information links* by which this can be achieved. Within each of the components *private* information links are defined to transfer information from one component to another. In addition, *mediating* links are defined to transfer information from the input interfaces of encompassing components to the input interfaces of the internal components, and to transfer information from the output interfaces of the internal components to the output interface of the encompassing components.

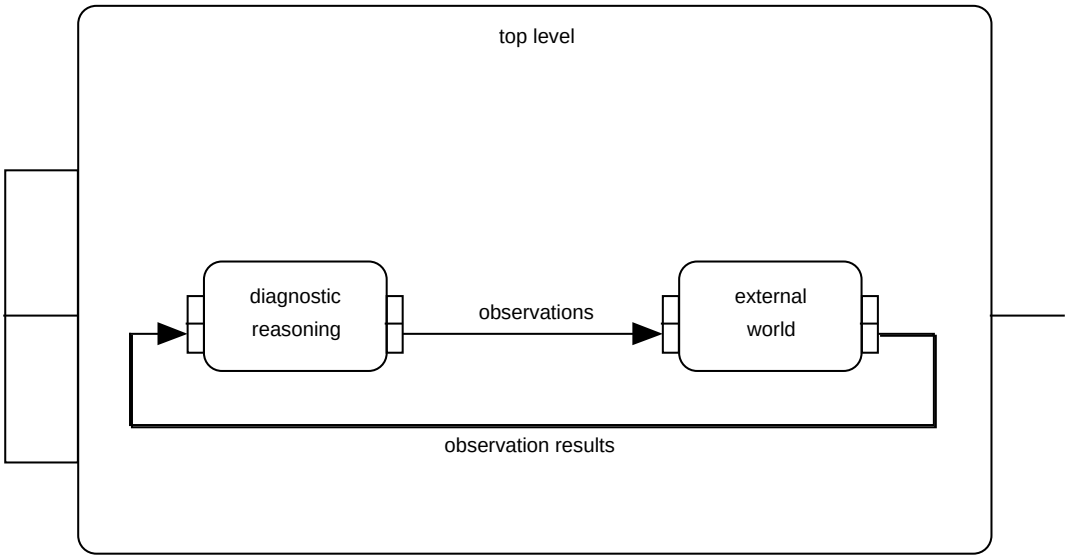


Figure 7 Information exchange within the top level process

As shown in Figure 7 two private links are defined at the top level: observations and observation results. The link observations transfers the list of observations to be performed (Selected Observations) from the lower level (called D object level) of the output interface of the component diagnostic reasoning to the lower level (called EW object level) of the input interface of the component external world. The link observation results transfers results of observations (Observation Result Info) from EW object level of the output interface of the component external world to D object level of the input interface of the component diagnostic reasoning.

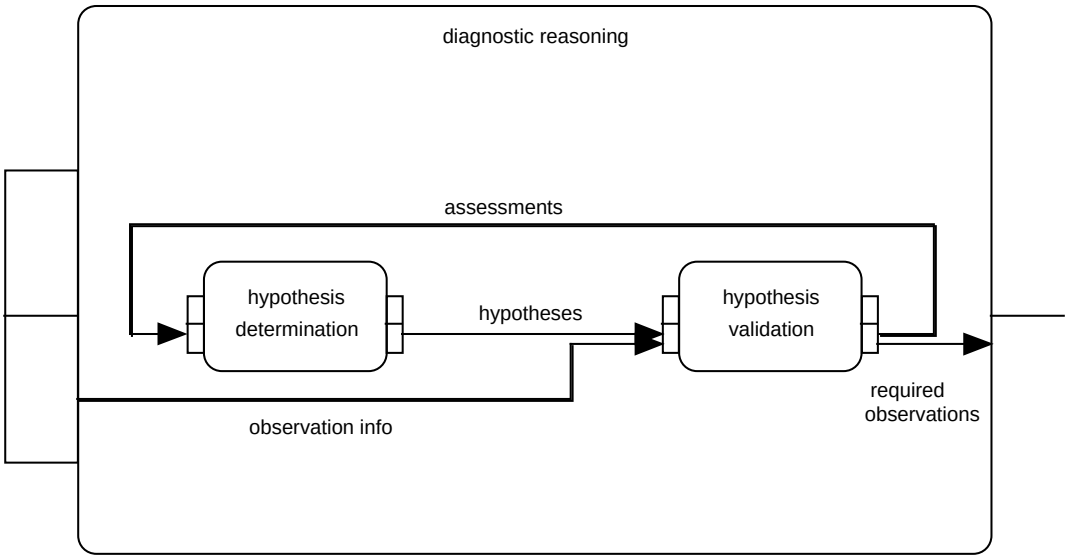


Figure 8 Information exchange within the diagnostic reasoning process

In Figure 8 four information links defined for the component diagnostic reasoning are depicted: two private and two mediating. The private links:

- the link hypotheses transfers Selected Hypotheses from the lower level (called HD object level) of the component hypothesis determination to the lower level (called HV object level) of the component hypothesis validation to become the hypotheses on which the diagnostic process is to focus,
- the link assessments transfers Assessed Hypotheses from level HV object level of the output interface of the component hypothesis validation to HD object level of the input interface of the component hypothesis determination.

The two mediating links:

- the link observation info transfers observation results from D object level of the input interface of the component diagnostic reasoning to HV object level of the component hypothesis validation,
- the link required observations transfers selected observations from HV object level of the component hypothesis validation to D object level of the output interface of the component diagnostic reasoning

Within the component hypothesis validation, see Figure 9, one private link and five mediating links are defined. The private link:

- the link performed obs transfers epistemic domain information (on the results of observations) from HE meta-level (the highest level of the output interface of hypothesis evaluation) of the output interface of the component hypothesis evaluation to HD object level of the input interface of observation determination

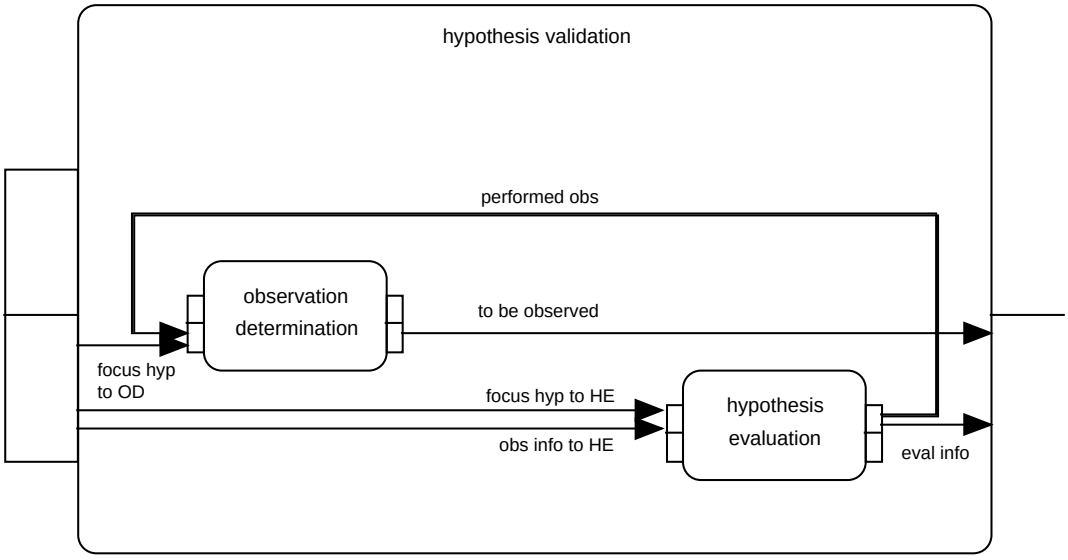


Figure 9 Information exchange within Hypothesis Validation

The five mediating links:

- the link focus hyp to OD transfers the hypotheses to be validated, Focussed Hypotheses, from HV object level of the input interface of the component hypothesis validation to OD object level of the component observation determination,
- the link focus hyp to HE transfers the hypotheses to be validated, Focussed Hypotheses, from HV object level of the input interface of the component hypothesis validation to HE meta-level of the component hypothesis evaluation,
- the link obs info to HE transfers the results of observations, Observation Result Info, from HV object level of the input interface of the component hypothesis validation to HE meta-level of the input interface of the component hypothesis evaluation,
- the link to be observed transfers Selected Observations from OD object level of the output interface of the component observation determination to HV object level of the output interface of the component hypothesis validation,
- the link eval info transfers the result of hypothesis evaluation, namely Assessed Hypotheses from HE meta-level of the component hypothesis evaluation to HV object level of the output interface of the component hypothesis validation

Task control knowledge

Components may be activated sequentially or they may be continually capable of processing new input as soon as it arrives (*awake*). The same holds for information links: information links may be explicitly activated or they may be awake. *Task control knowledge* specifies

under which conditions which components and information links are active (or made awake). Evaluation criteria, expressed in terms of the evaluation of the results (success or failure), provide a means to guide further processing.

In a design, task control knowledge specifies when and how processes are to be performed and evaluated. Goals of a process are defined by the *task control foci* together with the *extent* to which they are to be pursued. Evaluation of the success or failure of a process's performance is specified by *evaluation criteria* together with an extent. Processes may be performed in sequence or in parallel, some may be continually performed (e.g., reacting to new input as soon as it arrives), some are to be explicitly activated.

The two main processes distinguished for the example, the diagnostic reasoning process and the external world, are both designed to react to new input as soon as it arrives. Both processes are performed in parallel. Diagnostic reasoning, however, as modelled in this example, entails determination of hypotheses and validation. These processes are performed in sequence: once a set of hypotheses has been selected as a focus for hypothesis validation, hypothesis validation analyses the set. The result of validation is new input for hypothesis determination. The more precise specification of task control knowledge structures is addressed in Section 3.2.

3.2 Knowledge composition

Knowledge composition identifies the knowledge structures at different levels of (knowledge) abstraction, and describes how a knowledge structure can be defined in terms of lower level knowledge structures. The knowledge abstraction levels may correspond to the process abstraction levels, but this is not often the case; often the matrix depicted in Figure 2 shows more than a one to one correspondence between process abstraction levels and knowledge abstraction levels.

3.2.1 Identification of knowledge structures at different abstraction levels

The two main structures used as building blocks to model knowledge are: *information types* and *knowledge bases*. Knowledge structures can be identified and described at different levels of abstraction. At the higher levels the details can be hidden. The resulting levels of knowledge abstraction can be distinguished for both information types and knowledge bases.

Information types

An information type defines an *ontology* (lexicon, vocabulary) to describe objects or terms, their sorts, and the relations or functions that can be defined on these objects. Information types are defined as signatures (sets of names for sorts, objects, functions, and relations) for order-sorted predicate logic. Information types can be specified in graphical form (see (Jonker and Treur, 1999), or in formal textual form. For the example diagnostic reasoning

task the following information types have been specified in textual form. The attribute information types is used to import other information types. Via the attribute meta-descriptions all atoms that can be built by the referenced information type are imported in the indicated sort. For example,

```
meta-descriptions
                    domain_hypotheses      :      HYPOTHESIS ;
```

specifies that all atoms that can be formed using the information type domain_hypotheses are included as objects or terms in the sort HYPOTHESIS. This language construct is used to define object-meta relations in the reasoning process.

Generic information types on hypotheses:

```
information type  hypotheses_sorts
    sorts       HYPOTHESIS ;
end information type

information type  meta_domain_hypotheses
    information types    hypotheses_sorts ;
    meta-descriptions
        domain_hypotheses :    HYPOTHESIS ;
end information type

information type  assessed_hypotheses
    information types    meta_domain_hypotheses;
    relations  tried, rejected, confirmed     :    HYPOTHESIS ;
end information type

information type  selected_hypotheses
    information types       meta_domain_hypotheses ;
    relations
        to_be_validated ,
        has_been_focus      :    HYPOTHESIS ;
        subhypothesis :  HYPOTHESIS * HYPOTHESIS;
end information type
```

Generic information types on symptoms:

```
information type  symptoms_sorts
    sorts       SYMPTOM ;
```

end information type

information type meta_domain_symptoms

information types symptoms_sorts ;

meta-descriptions

domain_symptoms : SYMPTOM ;

end information type

information type selected_observations

information types meta_domain_symptoms; meta_domain_hypotheses

relations to_be_observed : SYMPTOM ;

relevant_observation_for : SYMPTOM * HYPOTHESIS;

end information type

information type observation_results

information types domain_symptoms ;

end information type

information type value_signs

sorts SIGN

objects pos, neg : SIGN ;

end information type

information type observation_information

information types meta_domain_symptoms , value_signs ;

relations observed : SYMPTOM * SIGN ;

end information type

Domain-specific information types on hypotheses:

information type domain_hypotheses

information types hypotheses_sort;

objects fridge_problem, electricity_problem, cooling_problem,

no_power_supply, broken_bulb, broken_pump, broken_cooling_system: HYPOTHESES;

end information type

Domain-specific information types on symptoms:

information type domain_symptoms

information types symptoms_sort;

objects light, cold, noise: SYMPTOM;

end information type

Knowledge bases

Knowledge bases use ontologies defined in information types. Which information types are used in a knowledge base is defined by a relation between information types and knowledge bases. In detailed design, knowledge bases are specified in order-sorted predicate logic form, normalised to a classical rule format (implications between conjunctions of literals), as shown below Figure 11. Knowledge bases can also be specified in conceptual pre-formal manners, for example in graphical forms. Graphical representations of knowledge bases for the example diagnostic reasoning task are as follows. In Figure 10 the causal relations between faults and observations are depicted.

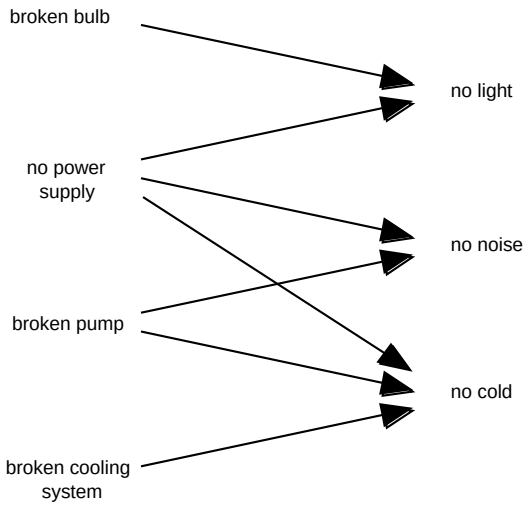


Figure 10 The causal relations between faults and observations

As mentioned in the problem description, for simplicity's sake, only single faults are considered. If any one of the faults occurs, there is a *fridge problem*. If the fridge either has a broken bulb or there is no power supply, the fridge is said to have an *electricity problem*. If either the pump or the cooling system is broken, the fridge is said to have a *cooling problem*. In Figure 11 this taxonomy of types of problems is depicted.

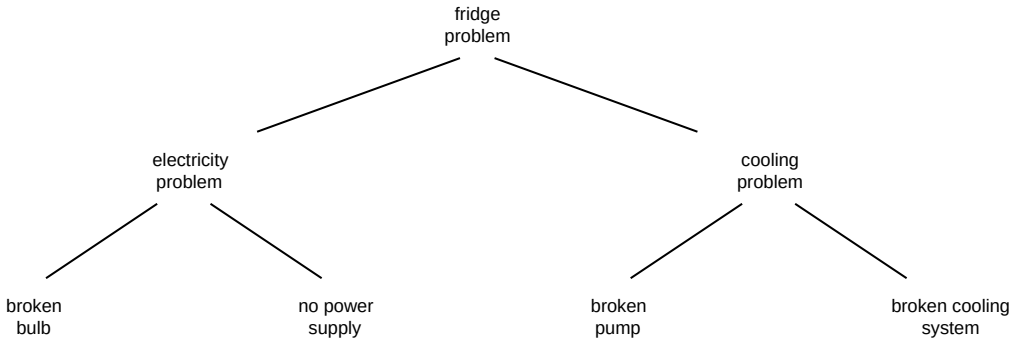


Figure 11 Taxonomy of types of fridge problems

The object level domain knowledge can be modelled in a *causal* (i.e., faults imply observations, as depicted in Figure 10) or *anti-causal* (i.e., observations imply faults) manner. For this example, the anti-causal manner has been chosen. The knowledge base anti causal fridge knowledge consists of:

```
if  fridge_problem          and not  light          then  electricity_problem
if  fridge_problem          and not  cold
                            and  light              then  cooling_problem
if  electricity_problem     and not  cold           then  no_power_supply
if  electricity_problem     and  cold               then  broken_bulb
if  cooling_problem         and not  noise          then  broken_pump
if  cooling_problem         and  noise              then  broken_cooling_system

if  light                                           then not  electricity_problem
if  cold                                            then not  cooling_problem
if  not  cold               and  not light          then not  cooling_problem

if not  fridge_problem                              then not  electricity_problem
                                                          and not  cooling_problem
if not  electricity_problem                         then not  broken_bulb
                                                          and not  no_power_supply
if not  cooling_problem                             then not  broken_pump
                                                          and not  broken_cooling_system
```

The component hypothesis determination uses the following knowledge bases:

hypothesis_refinement_kb *(domain independent knowledge)*

```
if  confirmed(H:HYPOTHESIS)
  and  subhypothesis_of(H1:HYPOTHESIS, H:HYPOTHESIS)
  and  not  tried(H1:HYPOTHESIS)
then  focus_hypothesis(H1:HYPOTHESIS)
```

subhypotheses_kb *(domain specific knowledge)*

```
subhypothesis_of(broken_bulb         , electricity_problem)
subhypothesis_of(no_power_supply  , electricity_problem)
subhypothesis_of(broken_pump       , cooling_problem)
subhypothesis_of(broken_cooling_system , cooling_problem)
subhypothesis_of(cooling_problem    , fridge_problem)
subhypothesis_of(electricity_problem, fridge_problem)
```

The domain specific knowledge base subhypotheses_kb represents the knowledge depicted in a graphical form in Figure 11 (the taxonomy). The generic rule in the domain independent knowledge base hypothesis_refinement_kb specifies that each of the confirmed children of a node become a focus hypothesis, if not already validated.

The component observation determination uses the following knowledge bases:

generic_obs_determination_kb *(domain independent knowledge)*

```
if  focus_hypothesis(H:HYPOTHESIS)
   and  relevant_observation_for(S:SYMPTOM, H:HYPOTHESIS)
then  relevant_observation(S:SYMPTOM)

if   relevant_observation(S:SYMPTOM)
   and not observed(S:SYMPTOM, pos)
   and not observed(S:SYMPTOM, neg)
then  to_be_observed(S:SYMPTOM)
```

obs_relevance_kb *(domain specific knowledge)*

```
relevant_observation_for(light    , electricity_problem)
relevant_observation_for(cold    , cooling_problem)
relevant_observation_for(cold    , broken_lamp)
relevant_observation_for(cold    , no_power_supply)
relevant_observation_for(noise , broken_pump)
relevant_observation_for(light    , broken_pump)
relevant_observation_for(noise , broken_cooling_system)
```

These knowledge bases specify that the observations that are relevant for at least one of the focus hypotheses are selected, unless they have already been performed.

3.2.2 Composition of knowledge structures

Information types can be composed of more specific information types, following the principle of compositionality discussed above. Similarly, knowledge bases can be composed of more specific knowledge bases. The compositional structure is based on the different levels of knowledge abstraction distinguished, and results in information and knowledge hiding.

Composition of information types

The relations between the information types distinguished above and generic information types distinguished for diagnosis, are depicted below in Figures 12 and 13. The information types selected hypotheses, assessed hypotheses and focussed hypotheses, see Figure 12, refer to the information type meta domain hypotheses. The information type meta-domain hypotheses refers to the information types hypotheses sorts and domain hypotheses. Note in this respect the meta-object distinction meta-domain hypotheses and domain hypotheses.

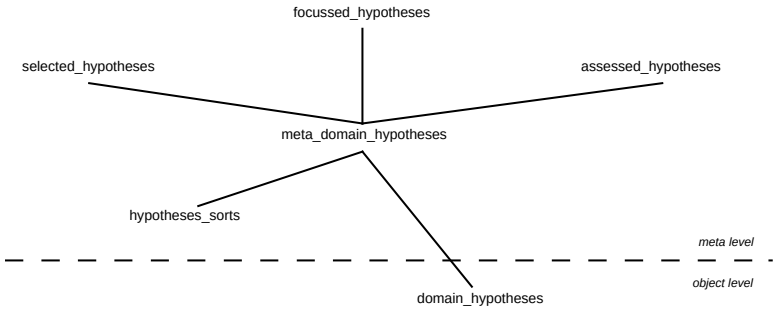


Figure 12 Composition of information types: hypotheses

The information types predicted symptoms, observation information and selected obervations refer to the information type meta-domain symptoms in a similar way, see Figure 13. The information types predicted symptoms and observation information both refer to value signs.

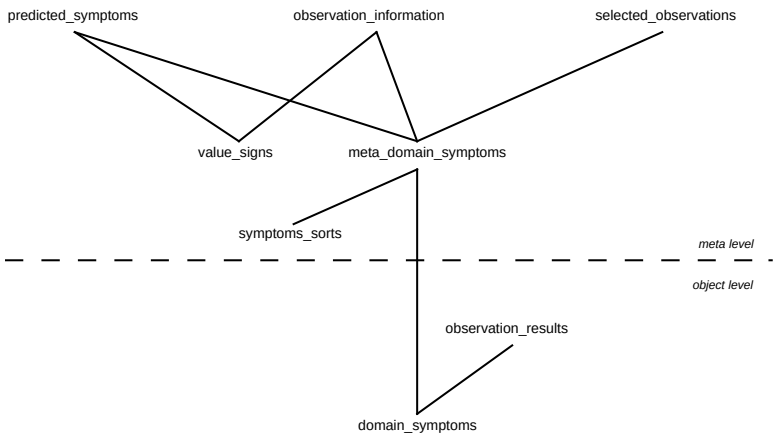


Figure 13 Composition of information types: observations

The information types predicted symptoms, selected observations and observation information all refer to the information type meta-domain hypotheses. Information type observation results refers to domain symptoms. Only domain symptoms and observation results are on the same object level, all other information types are at the same meta-level.

Composition of knowledge bases

The knowledge base hypothesis_determination_kb is composed of the generic knowledge base hypothesis_refinement_kb and the domain-specific knowledge base subhypotheses_kb. The knowledge base observation_determination_kb is composed of the generic knowledge base generic_obs_determination_kb and the domain-specific knowledge base obs_relevance_kb.

3.2.3 Task control knowledge

Processes at different abstraction levels can have different degrees of autonomy. For example, to constrain behaviour the following forms of control can occur:

- *Fully decentralised control*
  Processes at the lowest process abstraction levels are all autonomous (i.e., not constrained by control from the higher levels) and the behaviour of the processes at the higher abstraction levels emerges on the basis of the behaviour of the processes at the lower levels (and the composition relation defined by the information links).
- *Fully centralised control*
  The top level process has control knowledge that constrains the behaviour of the processes at the lower level of process abstraction (e.g., by a constraint prescribing a sequence of activation), which in their turn have control knowledge that constrains the processes at the levels below, and so on.
- *Centralised top level, decentralised lower level control*
  The top level has centralised control of the processes at the level of process abstraction level (just) below it and processes at the lowest levels of process abstraction are autonomous.
- *Decentralised top level, centralised lower level control*
  Control is minimal at the top level (e.g., agents are completely autonomous), but at the lower levels (within the agents) more centralised forms of control are used to obtain coherent behaviour (the agents themselves have control over their activities). This form of control is often used within multi-agent systems.

Different variants of control can be modelled within DESIRE, including all types of control mentioned above. Whether or not control knowledge is modelled to constrain the behaviour of the sub-processes can be decided independently for each of the processes at each level of abstraction. Together with the information links, the control knowledge defines the process composition relation.

Task control knowledge specifies control of a component. A component can be in one of three *states*: it can be active, awake, or idle. A component in state idle is inactive. An active or awake component is actively pursuing a strategy defined by its task control focus and extent.

A *task control focus* defines the focus of the process: processes can have different foci, specified as task control foci. Dynamic selection of a task control focus, is one of the ways in which a process can be controlled. To each task control focus a specific set of *targets* can be associated. These are the outputs the process tries to determine. An *extent* specifies to which extent targets associated to a task control must be derived; see Figure 14.

If an *active* component *succeeds* or *fails* to derive the targets specified in its task control focus to a given extent, it becomes idle. An *awake component* is a component that is continually capable of deriving new information. Its task control focus and extent are used to focus the reasoning process in the same way as the task control focus and extent are used to focus the reasoning in active components. Links can be either awake (in which case information is transferred as soon as it has become available), uptodate (in which case information has just been transferred). A link or component in state awake remains in this state continually, even if the component or link has nothing to do (in this way they are stand-by). A component or link in state awake reacts to arriving information immediately (event-driven). A component in state active and link in state uptodate becomes idle as soon as no new information can be derived (termination). A component or link in state idle does not react to arriving information. It can only react if its state is explicitly changed to awake or active, respectively uptodate.

extent	*to be derived*
all p	all possible targets
every	every target
any	any target
any new	any target not previously derived

Figure 14 Extents

The names of task control foci are part of the public task information in a component specification. The *initial task control focus* and the *initial extent* can be specified (the initial task information, as part of private task information) as well as which targets initially are associated to which task control focus (*initial targets*): initial kernel information, as part of private kernel information. A target specifies whether its aim is to confirm, determine or reject a specific output atom. Evaluation criteria can be specified to assess a component's results. These may be the same as task control foci, or they may differ. Also to evaluation criteria specific sets of targets can be associated. Different evaluation criteria can be used to determine the status of a component's process, each with different implications: depending on which evaluation criteria have been successfully achieved, or failed, one or more components may be activated (made active or awake).

In the diagnostic reasoning example the component diagnostic reasoning has initial information about its task control focus diagnose fault and its extent, namely all p. This implies that the component will succeed if all possible targets associated to the task control focus diagnose fault have been derived. The definition of this information is included in the definition of diagnostic reasoning's private kernel information as initial kernel information: this specifies that the output atoms the component aims to determine are all atoms of the form diagnosis(H: HYPOTHESIS) for some instantiation of H: HYPOTHESIS for the task control focus diagnose fault. This is specified by the expression: diagnosis(H : HYPOTHESES) : confirm, where confirm is the *target type.* Note that targets are specified one level higher than the output atoms to which they refer: target information is not information about the world but about the component's process: a target describes meta-information expressed by a meta-atom of the form target(diagnose_fault, diagnosis(H:HYPOTHESIS), confirm).

Instances of task control knowledge of the diagnostic reasoning example are used to illustrate task control specifications. Continual activity of both the component diagnostic reasoning and the component external world, and the two links observations and observation results, is specified as task control knowledge of the component top level.

if start
then next_component_state(diagnostic_reasoning, **awake**)
and **next_component_state**(external_world, **awake**)
and **next_link_state**(observations, **awake**)
and **next_link_state**(observation_results, **awake**)

The component diagnostic reasoning is made awake: the system is to continually react to new information in its effort to confirm all possible hypotheses. The external world is assumed to be continually awake, capable of executing an observation as soon as it arrives. Information provided by one of the two components is immediately transferred to the other by the respective link which is awake.

An example of *task control knowledge* within the component diagnostic reasoning is as follows:

if start
then next_component_state(hypothesis_determination, **active**)
and next_link_state(assessments, **uptodate**)
and next_task_control_focus(hypothesis_determination, determine_hypos)
and next_extent(hypothesis_determination, **any_new**)

This rule states that when activated (in the sense of active or awake), the component diagnostic reasoning activates its sub-component hypothesis determination with the state active, with the task control focus determine hypos and extent any new. In this rule, task control focus and extent do not actually need to be specified, as they never change during the process; they can be specified as initial task information. Another example of task control knowledge of the component diagnostic reasoning is:

if component_state(hypothesis_determination, **idle**)
and previous_component_state(hypothesis_determination, **active**)

and evaluation(hypothesis_determination, hypos_determined, **any**, **succeeded**)
then next_component_state(hypothesis_validation, **awake**)
and next_link_state(hypotheses, **uptodate**)

This statement specifies that if the component hypothesis determination terminates and succeeds in deriving any target associated to hypos determined (an evaluation criterion), then, at the next point in time, the component hypothesis validation, has state **awake**. In addition the link between hypothesis determination and hypothesis validation, has become **uptodate.**

Task control knowledge constrains the process states of components. Typically, in the current version of the DESIRE software environment, task control knowledge is specified according to the pattern

previous state & current state ± next state

This form (actually a form of executable temporal logic; cf. (Barringer et al., 1996)), enables direct computation of the next control state from the current and previous control state. In the near future, extensions of this format (e.g., by adding intermediate information types) will be supported.

3.3 Relation between process composition and knowledge composition

Each process in a process composition uses knowledge structures. Which knowledge structures (information types and knowledge bases) are used for which processes is defined by the relation between process composition and knowledge composition. The cells within the matrix depicted in Figure 2 define these relations.

For the example diagnostic reasoning task the knowledge base related to the primitive component hypothesis evaluation is anticausal_fridge_kb. The knowledge base related to hypothesis_determination is hypothesis_determination_kb; the knowledge base related to observation_determination is observation_determination_kb

4 Design rationale

One of the parts of the *design rationale* describes verification of the relevant properties of the designed system in relation to the design requirements identified in the problem description. Also the assumptions under which these properties hold are made explicit in the design rationale. Important design decisions are specified, together with some of the alternative choices that could have been made and the arguments in favour of and against the different options. At the operational level the design rationale includes decisions based on operational considerations, such as the choice to implement a parallel process on one or more machines, depending on the available capacity.

For verification, the possible states of the world (world situations) taken into account are depicted in Figure 15.

atoms	*possible world states*						
light	false	false	false	true	true	true	true
noise	false	true	false	false	true	true	false
cold	true	true	false	false	false	true	true
fridge problem	true	true	true	true	true	false	false
electricity problem	true	true	true	false	false	false	false
cooling problem	false	false	false	true	true	false	false
broken bulb	true	true	false	false	false	false	false
no power supply	false	false	true	false	false	false	false
broken pump	false	false	false	true	false	false	false
broken cooling system	false	false	false	false	true	false	false

Figure 15 Possible world states for the example domain

It is easy to verify that this anti-causal knowledge is *correct* with respect to the possible world states depicted in Figure 15, in the sense that for given observation results, conclusions drawn by means of this knowledge are true in the world state in which the observations were performed. Moreover, the knowledge is *decisive* in the sense that if it is known whether there is a fridge problem, and sufficient observation information is available, then for each of the causes it can be derived whether or not it is true (one of the variants of completeness; see (Treur and Willems, 1994)).

A trivial approach would be to perform all possible observations and then draw a conclusion on the hypotheses (e.g., using the knowledge base above). For practical applications, such a trivial approach is not satisfactory: many observations would have to be performed that do not contribute to the solution. The challengelies mainly in the question which strategy can be followed to obtain observation information, sufficient to determine which hypotheses are true and which are false, but as economically as possible.

One strategy for the strategic reasoning processes described, in the literature is called *hierarchical classification.* This strategy uses a taxonomy of types of problems (also called *abstract hypotheses*) of different levels of abstraction like the one used in the example model for diagnostic reasoning. The strategy of hypothesis determination is to first determine hypotheses at the highest level in the taxonomy, and depending on which of these abstract hypotheses are confirmed (by validation), proceed by selection of more specific hypotheses. Thus, if an abstract hypothesis is confirmed, then the next hypotheses to focus on are its

children in the taxonomy. The *specific hypotheses* for the diagnostic process as a whole are the hypotheses at the bottom of the taxonomy.

The abstract hypotheses in the taxonomy play two intermediary roles during the diagnostic process:

- they serve as intermediate results in the object level reasoning (e.g., using the knowledge base above), and
- they play an important strategic role within the hypothesis determination task (meta-level reasoning about focussing the diagnostic process).

A confirmed abstract hypothesis defines a sub-taxonomy (below), that can be further pursued by selecting its children (sub-hypotheses in the taxonomy) as the next hypotheses to be validated. The children of non-confirmed hypotheses are not further pursued. In this way each of the intermediate outcomes of the reasoning process (a confirmed abstract hypothesis) implies control of the direction of search. This hierarchical strategy of hypothesis determination is more economical than treating all specific hypotheses in sequence. Analysing all specific hypotheses, for example, for a binary tree of depth n entails validation of 2^n specific hypotheses, whereas for hierarchical classification following the taxonomy from top to bottom, two hypotheses per level need to be analysed, entailing validation of only $2n$ hypotheses for the whole process.

5 The DESIRE software environment

The DESIRE development method is supported by the distributed DESIRE software environment. This environment includes tools to support system development during all phases of design. Graphical editors, for example, support specification of conceptual and detailed design of processes and knowledge. A detailed design is a solid basis to develop an operational implementation in any desired environment. An implementation generator supports prototype generation of both partially and fully specified models. The code generated by the implementation generator can be executed in a distributed execution environment, which runs on different platforms: UNIX-based and Windows-based systems.

6 Control of the Dyanamics of Reasoning by Dynamic Targets and Dynamic Assumptions

Control of reasoning processes can be imposed in different manners. One option is related to the process composition and uses task control knowledge as presented above to control the global phases (specified by different components), and task control foci in a reasoning process. In addition to this global form of control of reasoning, also control at a more detailed level is possible. An option for more fine-grained control is to dynamically generate goals (targets) for the reasoning process within a (primitive) component, thus supporting dynamic

control of limited reasoning within a component. Another option for more fine-grained control is to dynamically generate additional presuppositions (assumptions) for the reasoning process in a component. In this section the control of reasoning by dynamic targets and by dynamic assumptions is discussed.

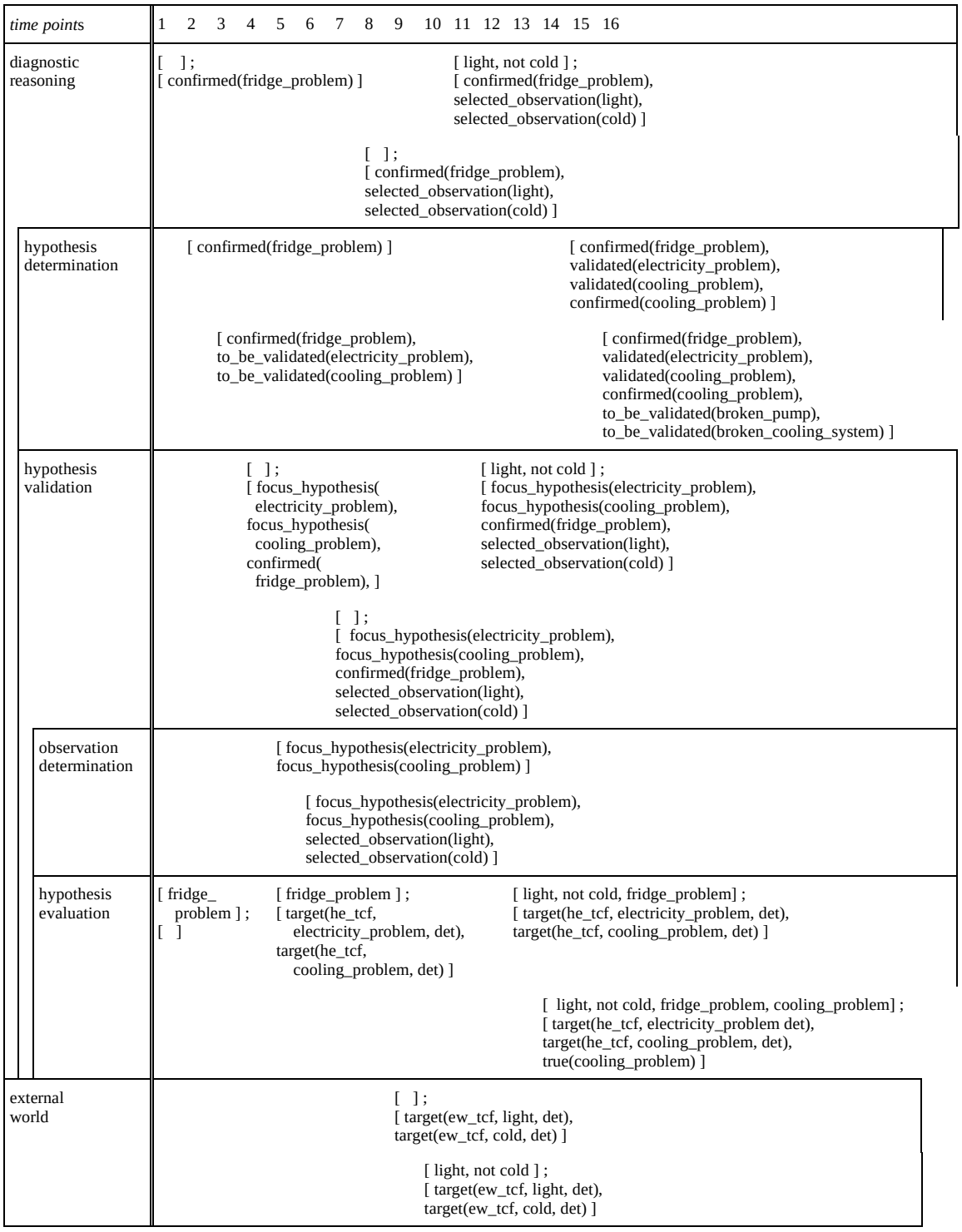
6.1 Control by dynamic generation of targets

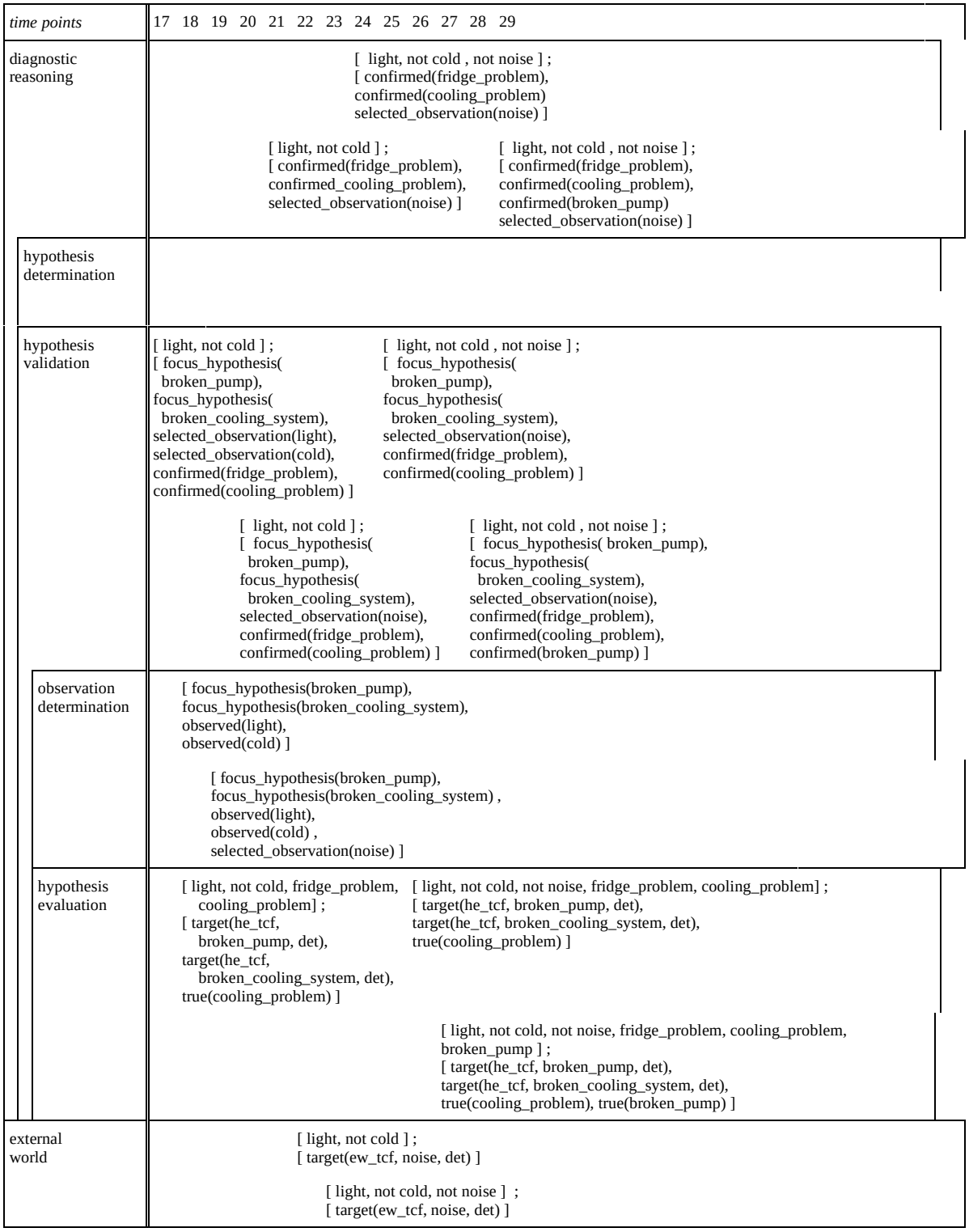
In this section the example of refridgerator diagnosis is used to illustrate the use of dynamic targets to control reasoning patterns in a fine-grained manner.

First example trace

The first example reasoning trace considered is depicted in Figure 16. The trace starts when the system is informed that there are problems with the fridge (1). This information is transferred to the component hypothesis determination (2), where, based on the taxonomy of hypotheses, two (abstract) hypotheses to be validated (electricity problem, cooling problem) are determined (3). These focus hypotheses are transferred to the component hypothesis validation (4), and within this component to both the components observation determination and hypothesis evaluation (5). In the latter component they serve as targets: the reasoning process within the component is limited to deriving these outputs only; however, in the beginning there is not enough observation information available to derive either one of these targets. In observation determination, based on the hypotheses in focus, two observations to be performed (to observe light, cold) are determined (6), which are transferred to the output interface of hypothesis validation (7), and from there to the output interface of diagnostic reasoning (8).

Figure 16 First example trace description




time points
17 18 19 20 21 22 23 24 25 26 27 28 29
diagnostic reasoning
[light, not cold , not noise] ;
[confirmed(fridge_problem),
confirmed(cooling_problem)
selected_observation(noise)]
[light, not cold] ;
[confirmed(fridge_problem),
confirmed_cooling_problem),
selected_observation(noise)]
[light, not cold , not noise] ;
[confirmed(fridge_problem),
confirmed(cooling_problem),
confirmed(broken_pump)
selected_observation(noise)]
hypothesis determination
hypothesis validation
[light, not cold] ;
[focus_hypothesis(
broken_pump),
focus_hypothesis(
broken_cooling_system),
selected_observation(light),
selected_observation(cold),
confirmed(fridge_problem),
confirmed(cooling_problem)]
[light, not cold , not noise] ;
[focus_hypothesis(
broken_pump),
focus_hypothesis(
broken_cooling_system),
selected_observation(noise),
confirmed(fridge_problem),
confirmed(cooling_problem)]
[light, not cold] ;
[focus_hypothesis(
broken_pump),
focus_hypothesis(
broken_cooling_system),
selected_observation(noise),
confirmed(fridge_problem),
confirmed(cooling_problem)]
[light, not cold , not noise] ;
[focus_hypothesis(broken_pump),
focus_hypothesis(
broken_cooling_system),
selected_observation(noise),
confirmed(fridge_problem),
confirmed(cooling_problem),
confirmed(broken_pump)]
observation determination
[focus_hypothesis(broken_pump),
focus_hypothesis(broken_cooling_system),
observed(light),
observed(cold)]
[focus_hypothesis(broken_pump),
focus_hypothesis(broken_cooling_system) ,
observed(light),
observed(cold) ,
selected_observation(noise)]
hypothesis evaluation
[light, not cold, fridge_problem,
cooling_problem] ;
[target(he_tcf,
broken_pump, det),
target(he_tcf,
broken_cooling_system, det),
true(cooling_problem)]
[light, not cold, not noise, fridge_problem, cooling_problem] ;
[target(he_tcf, broken_pump, det),
target(he_tcf, broken_cooling_system, det),
true(cooling_problem)]
[light, not cold, not noise, fridge_problem, cooling_problem,
broken_pump] ;
[target(he_tcf, broken_pump, det),
target(he_tcf, broken_cooling_system, det),
true(cooling_problem), true(broken_pump)]
external world
[light, not cold] ;
[target(ew_tcf, noise, det)]
[light, not cold, not noise] ;
[target(ew_tcf, noise, det)]

The observations to be performed, are transferred to the component external world (9), where they are actually performed (10). The observation results (light, not cold) are transferred to the component diagnostic reasoning (11), and within this component to hypothesis validation (12) and further down to the lower process abstraction level in hypothesis evaluation (13). Given the observation information (light, not cold), this component (which has electricity problem and cooling problem as targets) is able to derive that one of the abstract hypotheses (cooling problem) is true (14). This information is transferred to the component hypothesis determination, as is the information that both hypotheses in focus have been validated; based on this updated input, revision takes place, which leads to the retraction of the earlier derived conclusions on hypotheses to be validated (15).

After this revision, new (this time specific) hypotheses to be validated (broken pump and broken cooling system) are derived, based on the taxonomy of hypotheses (16), which again are transferred to hypothesis validation (17), and from there to the lower process abstraction levels of hypothesis evaluation and observation determination, where revision takes place (18). In observation determination a new observation to be performed (to observe noise) is found (19). Again, it is transferred to the output interface of hypothesis validation (20), and from there to the output interface of diagnostic reasoning (21).

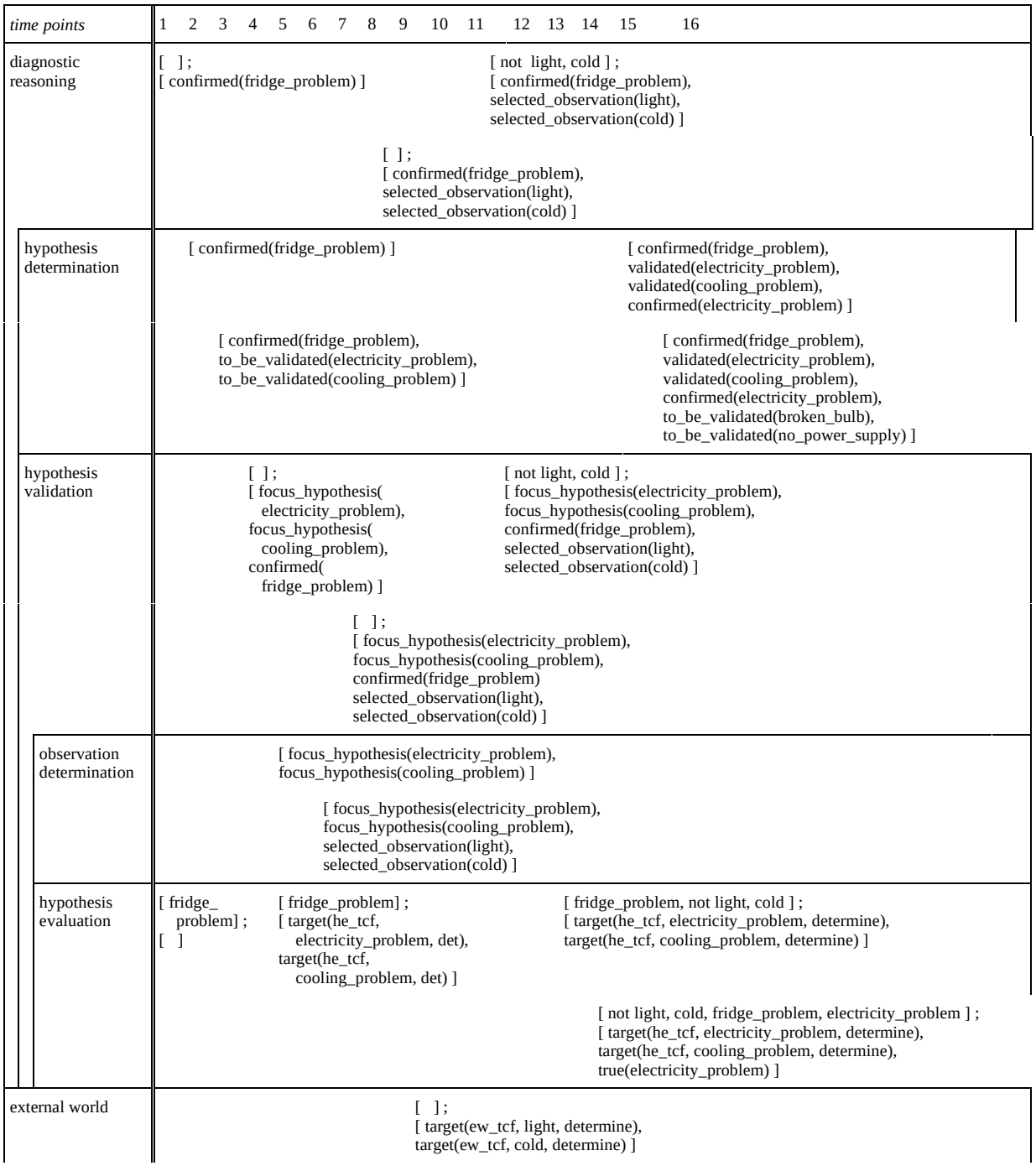
The new observation to be performed, is transferred to the component external world (22), where it is actually performed (23). The observation result (not noise) is transferred to the component diagnostic reasoning (24), and further down to hypothesis validation (25) and hypothesis evaluation (26). This time this component is able to derive that one of the specific hypotheses (broken pump) is true (27). This result is transferred up to the output interfaces of hypothesis validation (28) and diagnostic reasoning (29), respectively.

Second example trace

The second example reasoning trace considered in this chapter is depicted in Figure 17. Steps (1) to (9) are exactly the same steps as for the first trace. A difference occurs at step (10). This time the observations results are (not light and cold). From (11) to (18) a similar pattern as in the first trace is followed: after transfer of the observation results (12, 13), within the component hypothesis evaluation, which has electricity problem and cooling problem as its targets, the truth of the abstract hypothesis electricity problem is derived from the observation information (not light, cold) (14). This information is transferred to hypothesis determination entailing revision (15). After this the new (specific) hypotheses to be validated broken bulb and no electricity supply are derived, based on the taxonomy of hypotheses (16). These focus hypotheses are transferred down to the lower process abstraction level of hypothesis evaluation and observation determination, where revision takes place (17, 18). A difference occurs at (19). In observation determination no new observation to be performed is found (19). At the same time, the

component hypothesis evaluation is able to derive one of the specific hypotheses in focus (which, actually, are targets of hypothesis evaluation), namely broken bulb, without further observations. Therefore, this evaluation result is transferred up in the component hierarchy to hypothesis validation (20) and diagnostic reasoning (21), after which the diagnostic process stops.

Figure 17 Second example trace description



	[not light, cold] ; [target(ew_tcf, light, determine), target(ew_tcf, cold, determine)]

time points	17 18 19 20 21
diagnostic reasoning	[not light, cold] ; [confirmed(fridge_problem), confirmed(electricity_problem), confirmed(broken_bulb)]
hypothesis determination	
hypothesis validation	[not light, cold] ; [focus_hypothesis(broken_bulb), focus_hypothesis(no_power_supply), selected_observation(light), selected_observation(cold), confirmed(fridge_problem), confirmed(electricity_problem)] [not light, cold] ; [focus_hypothesis(broken_bulb), focus_hypothesis(no_power_supply), selected_observation(light), selected_observation(cold), confirmed(fridge_problem), confirmed(electricity_problem), confirmed(broken_bulb)]
observation determination	[focus_hypothesis(broken_bulb), focus_hypothesis(no_power_supply), observed(light), observed(cold)] [focus_hypothesis(broken_bulb), focus_hypothesis(no_power_supply) , observed(light), observed(cold)]
hypothesis evaluation	[not light, cold, fridge_problem, electricity_problem] ; [target(he_tcf, broken_bulb, determine), target(he_tcf, no_power_supply, determine), true(electricity_problem)] [not light, cold, fridge_problem, electricity_problem, broken_bulb] ; [target(he_tcf, broken_bulb, determine), target(he_tcf, no_power_supply, determine), true(electricity_problem), true(broken_bulb)]
external world	

Note that within the component hypothesis evaluation, the necessary information to derive broken bulb was already available at step (13). However, at that time broken bulb was not a target of this component, and therefore it was not derived. Only after the targets of hypothesis evaluation had been changed and included broken bulb (18), was it actually derived (19). This shows how targets influence the reasoning behaviour of the system.

6.2 Control by dynamic generation of assumptions

How to acquire and handle beliefs is an important but not simple task of an agent. In practice, information acquisition is often defeasible. Information acquired earlier may be found to be incorrect, and has to be retracted or revised. To support such processes the status of information can be modelled as well, for example whether or not a fact was assumed, or observed, or which agent communicated the fact. The decision of an agent to actually believe acquired information may depend on an estimation of the degree to which the source of the information is deemed to be trustworthy. Therefore different beliefs of an agent may have a different status, and the agent has to be prepared to revise its beliefs in the light of newly acquired information anyway. A possible pattern of strategic reasoning is the following:

- identify the *required* information
- determine the *method to acquire* the required information; for example, one of
  - derive information in a *deductive* manner from available information
  - determine an appropriate *assumption*, and make this assumption
  - acquire additional information by *observation* (in interaction with the world)
  - acquire additional information by *communication* (ask another agent)
- *apply* the chosen method for information acquisition
- *verify* the obtained information in the light of other available information
- *integrate* the new information in the available information

In this section a reasoning method in which assumptions are dynamically added and retracted (sometimes called hypothetical reasoning), is discussed. The reasoning method is illustrated by a simple example of diagnostic reasoning on malfunctioning cars. Reasoning with and about assumptions entails deciding about a set of assumptions to be assumed for a while (reasoning *about* assumptions), and deriving which facts are logically implied by this set of assumptions (reasoning *with* assumptions). The derived facts may be evaluated; based on this evaluation some of the assumptions may be rejected and/or a new set of assumptions may be chosen (reasoning *about* assumptions). As an example, if an assumption has been chosen, and the facts derived from this assumption contradict information obtained from a different source (e.g., by observation), the assumption may be rejected and the converse may be assumed.

Reasoning with and about assumptions is a reflective reasoning method. It proceeds by the following alternation of object level and meta-level reasoning, and upward and downward reflection:

- inspecting the information currently available (epistemic upward reflection),
- determining a set of assumptions (meta-level reasoning),
- temporarily assuming this set of assumptions (downward reflection of assumptions),

- deriving which facts follow from this assumed information (in the object level reasoning)
- inspecting the information currently available (epistemic upward reflection),
- evaluating the derived facts (meta-level reasoning)
- deciding to reject some of the assumptions and/or to choose a new set of assumptions based on this evaluation (meta-level reasoning).

and so on

As an example, if an assumption 'a is true' has been chosen, and the facts derived from this assumption contradict information that is obtained from a different source, the assumption 'a is true' may be rejected and the converse 'a is false' may be assumed. This reasoning pattern also occurs in diagnostic reasoning based on causal knowledge (discussed below) this reasoning pattern occurs.

6.2.1 Car diagnosis based on causal knowledge

In this section a simple diagnostic reasoning pattern on car malfunctioning is analysed. The causal knowledge on the domain of cars depicted in Figure 18 is used:

- if the battery is empty
  then the lights do not work
  and the car will not start
- if the sparking-plugs are tuned up badly
  then the car will not start

The causal knowledge could be easily extended, but for this example this knowledge suffices.

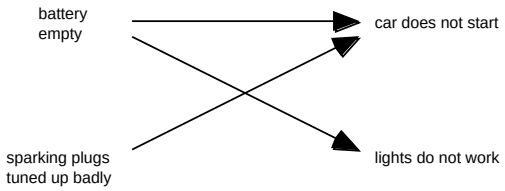


Figure 18 Causal knowledge for car diagnosis

At the meta-level the diagnostic reasoning process focusses on finding out whether an empty battery can be excluded as the cause of the problems. The following (simplified) meta-knowledge is used to reason about hypotheses: to propose hypotheses on which to focus, and to reject them if possible:

- if it has been observed that the car does not start
  and it is not known whether the hypothesis 'the battery is empty' holds

then ‘the battery is empty’ is an adequate hypothesis on which to focus

- if it has been observed that the car does not start
  and it is true that the battery is non-empty
  and it is not known whether the hypothesis ‘the sparking-plugs are tuned up badly’ holds
  then ‘the sparking-plugs are tuned up badly’ is an adequate hypothesis on which to focus

- if the focus is on a hypothesis X
  and, assuming X, it has been derived that Y is the case
  and it has been observed that Y is not the case,
  then the hypothesis X should be rejected

In the following section the generic model behind this reasoning pattern is introduced.

6.2.2 A generic model for reasoning with and about assumptions

The generic model for reasoning with and about assumptions consists of four primitive components: external world, predict observation results, assumption determination, assumption evaluation (see Figure 19). The first two of these components represent the object level, the last two the meta-level. The component observation result prediction reasons *with* assumptions, the two components assumption determination and assumption evaluation reason *about* assumptions.

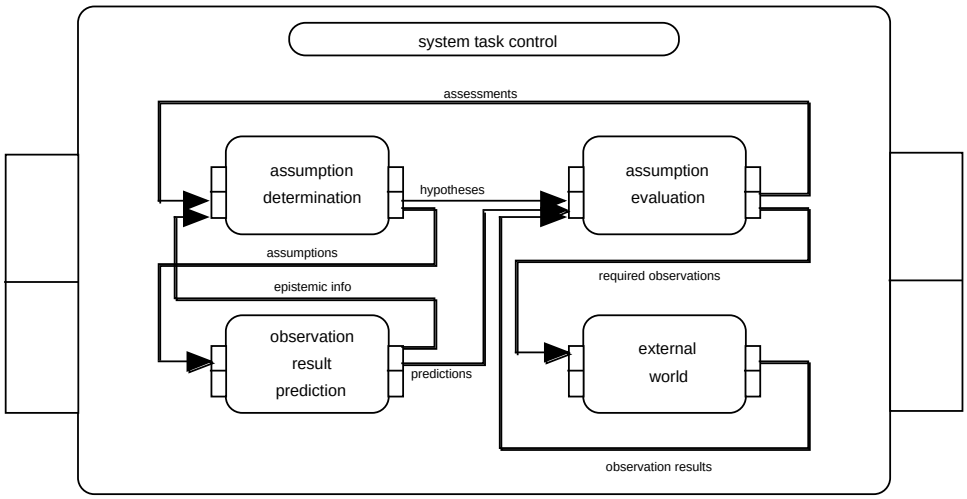


Figure 19 A generic model for reasoning with and about assumptions

The generic model is explained in this section for the domain of car diagnosis. In this example, the reasoning pattern starts with the information that the car will not start. Using

this information and the knowledge described above, the following reflective reasoning pattern is followed:

1. **component *assumption determination***
   From the observation that the car does not start and that it is as yet unknown whether the battery is empty, draw the conclusion at the meta-level that 'battery is empty' is an adequate hypothesis on which to focus
2. **information link *assumptions* (object-assumption)**
   Reflect this hypothesis downwards: introduce it at the object level as an assumption
3. **information link *hypotheses* (object-object)**
   Transfer the hypothesis to assumption evaluation
4. **component *observation result prediction***
   Draw the conclusion at the object level that the lights do not work
5. **information link *predictions* (epistemic-object)**
   Reflect upwards the information that object level reasoning has predicted that the lights do not work
6. **component *assumption evaluation***
   Draw the conclusion at the meta-level that the observation to find out whether the lights work is a useful observation to perform
7. **information link *observations* (object-target)**
   Reflect downwards the observation to be performed (as a target for the external world)
8. **component *external world***
   Perform an observation in the external world to find out whether the lights work
9. **information link *observation results* (epistemic-object)**
   Reflect the observation result upwards
10. **component *assumption evaluation***
    At the meta-level use the observation result that the lights work, and notice that the actual observation result contradicts the prediction on the observation. Draw the conclusion that the focus hypothesis 'battery is empty' should be rejected
11. **information link *assessments* (object-object)**
12. **component *assumption determination***

    and so on

Note the interaction between the two levels at points 5. and 9. (epistemic upward interaction of type epistemic-object), at point 2. (downward interaction to make an assumption: type object-assumption), and at point 7. (downward interaction to set a target: type object-target). These are the points in the traces , where interaction between levels takes place.

6.2.3 Overview of the components and information links

In this section a short overview is given of the components and information links of the generic model introduced in Section 1.2 and their instantiations for the domain of car diagnosis.

Overview of the components

The generic model is not specified in detail. Instead, the components and information links are depicted in Figure 19, and relevant parts of the detailed design are presented.

external world

This component is used for executing observations. It has no knowledge base.

Relevant *input atoms* (meta-level): target(observations, A:OA, determine)

Relevant *output atoms* (object level): car_starts, lights_work
(meta-level): true(A:OA), false(A:OA), known(A:OA)

observation result prediction

Based on the assumption, observations are predicted.

Relevant *input atoms* (object level): battery_empty, sparking_plugs_problem
(meta-level): assumption(A:IA, S:SIGN)

Relevant *output atoms* (meta-level): true(A:OA), false(A:OA), known(A:OA)

Relevant part of the *knowledge base*:

if battery_empty
then not lights_work
and not car _starts

if sparking_plugs_problem
then not car _starts

assumption determination

Based on the current state of the diagnostic process, assumptions are generated.

Relevant *input atoms*: rejected(H:HYPOTHESIS, S:SIGN),
has_been_considered(H:HYPOTHESIS),
observation_result(O:OBSERVATION, S:SIGN)

Relevant *output atoms*: poss_assumption(H:HYPOTHESIS, S:SIGN)

Relevant part of the *knowledge base*:

if observation_result(car_starts, neg)
and not has_been_considered(battery_empty)
then poss_assumption(battery_empty, pos)

if rejected(battery_empty, pos)
and not has_been_considered(sparking_plugs_problem)
then poss_assumption(sparking_plugs_problem, pos)

if rejected(H:HYPOTHESIS, pos)
then poss_assumption(H:HYPOTHESIS, neg)

assumption evaluation

Based on the selected assumption, the predicted and actual observation result, an evaluation is made.

Relevant *input atoms*: assumed(H:HYPOTHESIS, S:SIGN),
predicted(O:OBSERVATION, S:SIGN),
observation_result(O:OBSERVATION, S:SIGN)

Relevant *output atoms*: rejected(H:HYPOTHESIS, S:SIGN),
has_been_considered(H:HYPOTHESIS)
to_be_observed(O:OBSERVATION)

Relevant part of the *knowledge base*:

if predicted(O:OBSERVATION, S:SIGN)
then to_be_observed(O:OBSERVATION)

if assumed(H:HYPOTHESIS, S:SIGN)
and predicted(O:OBSERVATION, pos)
and observation_result(O:OBSERVATION, neg)
then rejected(H:HYPOTHESIS, S:SIGN)

if assumed(H:HYPOTHESIS, S:SIGN)
and predicted(O:OBSERVATION, neg)
and observation_result(O:OBSERVATION, pos)
then rejected(H:HYPOTHESIS, S:SIGN)

if assumed(H:HYPOTHESIS, S:SIGN)
then has_been_considered(H:HYPOTHESIS)

Note that the knowledge base specified above only contains domain independent knowledge. This knowledge base is small: the example reasoning pattern can be generated but not much more. This could be easily extended.

Overview of the information links

The information links of the generic model for reasoning with and about assumptions are shortly described as follows.

assumptions **(type object-assumption)**

The truth values of instances of output atoms poss_assumption(H:HYPOTHESIS, S:SIGN) of the component assumption determination are transferred to the same truth values of input meta-facts assumption(H:IA, S:SIGN) of the component observation result prediction. As a result the hypothesis to which the assumption refers can be used in this component.

epistemic information **(type epistemic-object)**

The truth values of output meta-facts of the form true(O:OA) of the component observation result prediction are transferred to the same truth values of object level input atoms of the component assumption evaluation of the form known_to_hold(O:OBSERVATION, pos). Similarly, the truth values of output meta-facts of the form false(O:OBSERVATION) of the component observation result prediction are transferred to the same truth values of object level input atoms of the component assumption evaluation of the form known_to_hold (O:OBSERVATION, neg).

predictions **(type epistemic-object)**

The truth values of output meta-facts of the form true(O:OA) of the component observation result prediction are transferred to the same truth values of object level input atoms of the component assumption evaluation of the form predicted(O:OBSERVATION, pos). Similarly, the truth values of output meta-facts of the form false(O:OBSERVATION) of the component observation result prediction are transferred to the same truth values of object level input atoms of the component assumption evaluation of the form predicted(O:OBSERVATION, neg).

required observations **(type object-target)**

The truth values of the object level output atoms to_be_observed(O:OBSERVATION) of the component assumption evaluation are transferred to the same truth values of meta-level input atoms target(observations, O:OA, determine) of the component external world.

observation results **(type epistemic-object)**

This interaction transfers truth values of output meta-facts of the form true(O:OA) (resp. false(O:OA)) of the component external world to the same truth values of object level input atoms of the component assumption evaluation of the form observation_result(O:OBSERVATION, pos) (resp. observation_result(O:OBSERVATION, neg)).

hypotheses **(type object-object)**

The truth values of the object level output atoms of the form poss_assumption(H:HYPOTHESIS, S:SIGN) of the component assumption determination are transferred to the same truth values of object level input atoms assumed(H:HYPOTHESIS, S:SIGN) of the component assumption evaluation.

assessments **(type object-object)**

This interaction transfers truth values of object level output facts of the form rejected(H:HYPOTHESIS) and has_been_considered(H:HYPOTHESIS) of the component assumption

evaluation to the same truth values of identical object level input atoms of the component assumption determination.

6.2.4 The dynamics of the reasoning method

Task control knowledge controls the activation of the components. For instance, first the component assumption determination is activated, next the component observation result prediction; if this succeeds (which is the case in the example trace below), then the component assumption evaluation is made active. After activation of the component external world to perform the observation, the component assumption evaluation is again activated. An example trace of a part of such a reasoning pattern is depicted in the example in Figure 20 starting with the initial information in the component assumption determination that it has been observed that car starts is false and that the truth or falsity of the hypotheses batttery empty and sparking plugs problem have not, as yet, been determined.

Figure 20 Trace of a hypothetical reasoning process

time point	**external world**	**observation result prediction**	**assumption determination**	**assumption evaluation**
1			[observation_result(car_starts, neg), not has_been_considered(battery_empty), not has_been_considered(sparking_plugs_problem)]	
2			[observation_result(car_starts, neg), not has_been_considered(battery_empty), not has_been_considered(sparking_plugs_problem), poss_assumption(battery_empty, pos)]	
3		[battery_empty]; [assumption(battery_empty, pos), true(battery_empty)]		
4		[battery_empty, not lights_work]; [assumption(battery_empty, pos), true(battery_empty), false(lights_work)]		
5				[assumed(battery_empty, pos), predicted(lights_work, neg)]
6				[assumed(battery_empty, pos), predicted(lights_work, neg), to_be_observed(lights_work)]

```
7       [ ];
                [ target(observations, lights_work, determine) ]

8       [ lights_work ];
                [ target(observations, lights_work, determine),
                  true(lights_work) ]

9                                                                  [ assumed(battery_empty, pos),
                                                                     predicted(lights_work, neg),
                                                                     to_be_observed(lights_work)
                                                                   observation_result(lights_work, pos) ]

10                                                                 [ assumed(battery_empty, pos),
                                                                     predicted(lights_work, neg),
                                                                     to_be_observed(lights_work),
                                                                   observation_result(lights_work, pos),
                                                                     rejected(battery_empty, pos),
                                                                  has_been_considered(battery_empty) ]

11                                                  [ observation_result(car_starts, neg),
                                                      has_been_considered(battery_empty),
                                                      not has_been_considered(sparking_plugs_problem)
                                                      rejected(battery_empty, pos) ]

12                                                  [ observation_result(car_starts, neg),
                                                      has_been_considered(battery_empty),
                                                      rejected(battery_empty, pos),
                                                      poss_assumption(battery_empty, neg),
                                                      poss_assumption(sparking_plugs_problem, pos)]

13              [ not battery_empty,
                  sparking_plugs_problem ];
                        [ assumption(battery_empty, neg),
                          assumption(sparking_plugs_problem, pos)
                          false(battery_empty),
                          true(sparking_plugs_problem) ]

14              [ not battery_empty,
                  sparking_plugs_problem,
                  not car_starts];
                        [ assumption(battery_empty, neg),
                          assumption(sparking_plugs_problem, pos)
                          false(battery_empty),
                          true(sparking_plugs_problem),
                          false(car_starts)]
```

This example trace combines traces for the four components. For the object level components observation result prediction and external world the information states for two levels are depicted as:

```
                [<object level information state>];
                        [ <meta-level information state> ]
```

These meta-level information states show how the interaction between levels takes place. Their content is directly related to the content of the object level information state. For example, in the example trace, after the first activation (1) - (2) of the component assumption determination the information link assumptions is made uptodate. This means that at the next moment in time the meta-statement assumption(battery_empty, pos) is true in the meta-information state of observation result prediction (3). However, at the same moment the assumption is actually made: at the object level the atom battery_empty becomes true. This is an example of (downward) interaction between the levels. As a consequence the meta-atom true(battery_empty) is given truth value true in the meta-level information state (upward interaction between the levels). As soon as the information link becomes uptodate (i.e., at the next moment in time), this whole revision process is assumed to have finished. At this time point (3) only the result of the process of level interaction is visible, the different steps as sketched are not recorded separately. Therefore, the interaction between the levels is considered to take place instantaneously, as soon as new information arrives as input.

The same holds in the opposite direction. Based on the assumption battery empty the component observation result prediction derives that lights work is false (4). At the same time the related epistemic meta-atoms have been assigned their appropriate truth values; e.g., false(lights_work) gets truth value true, which, again, is the actual (upward) interaction between the levels. This meta-information is transferred to the component assumption evaluation by the information link predictions (5).

A next interaction between levels can be found after the component assumption evaluation has derived the atom to_be_observed(lights_work) (6). The information link required observations transfers this information to the meta-atom target(observations, lights_work, determine) of the component external world (7). This time the actual (downward) interaction between the levels immediately determines control of the the component. The effect of the target is that the process focusses on lights_work only and does not try to find truth values for other atoms. For example, if the component external world actually stands for a human observer, then the target tells him or her what to observe. If, instead, the external world is a reasoning component, then the target focuses the component's reasoning by a goal-directed inference strategy with the target as its goal.

The result of the observation is that lights_work becomes true in the object level information state of the component external world (8). Again, an upward level interaction from object level to meta-level takes place instantaneously: at the same moment true(lights_work) becomes true. This observation result is transferred to the component assumption evaluation (9).

A fifth example of level interaction in the example trace is the second time assumptions are made in the component observation result prediction (13) - (14). This time the earlier made assumption that battery empty is true is retracted. This takes place because, due to revision

within the component assumption determination, the earlier drawn conclusion poss_assumption(battery_empty, pos) is retracted, which means that it is assigned truth value unknown. This truth value is propagated through the link assumptions: the meta-level atom assumption(battery_empty, pos) of the object level component observation result prediction is assigned the truth value unknown, the effect of which is that within the same component the object level atom battery_empty is assigned the truth value unknown (downward level interaction). At the same time the meta-level atom assumption(battery_empty, neg) is provided as input, which by downward level interaction assigns the truth value false to the object level atom empty_battery (note that in this downward level interaction the truth value unknown for the object level atom empty_battery is overruled by the truth value false). Furthermore, the meta-level atom assumption(sparking_plugs_problem, pos) is provided as input, which, by downward level interaction assigns the truth value true to the object level atom sparking_plugs_problem. After all of these downward level interactions, the epistemic information at the meta-level is updated in an upward level interaction, finishing all level interaction, and resulting in the state at time point (13).

The generic model for reasoning with and about dynamic assumptions (based on temporal epistemic reflection), has been used to model, for example, default reasoning and reasoning based on the closed world assumption, in a large number of applications.

7 Discussion

As shown in this paper compositional DESIRE models specify processes and knowledge at different levels of abstraction. Information exchange between processes and process sequencing are explicitly defined at each of the levels distinguished. Different levels of abstraction within the knowledge composition structure information types and knowledge bases. Reuse of generic models within DESIRE is supported by their transparent compositional structure. The basic principles behind compositional multi-agent system development described in this paper (process and knowledge abstraction, compositionality, reusability, formal semantics, and formal evaluation) are principles generally acknowledged to be of importance in both software engineering and knowledge engineering. The operationalisation of these principles within a compositional development method for multi-agent systems is, however, a distinguishing element. This method is supported by a (graphical) software environment in which all three levels of design are supported: from conceptual design to implementation. Libraries of both generic models and instantiated components, of which a few have been highlighted in this paper, support system designers at all levels of design. Generic agent models, generic task models and generic models of reasoning patterns help structure the process of system design. Formal semantics provide a basis for methods for verification - an essential part of such a method.

A number of approaches to conceptual-level specification of multi-agent systems have been recently proposed. On the one hand, general-purpose formal specification languages stemming from Software Engineering are applied to the specification of multi-agent systems

(e.g., (Luck and d'Inverno, 1995) for an approach using Z). A compositional development method such as DESIRE is committed to well-structured compositional designs that can be specified at a higher level of conceptualisation than in Z or VDM and can be implemented automatically using automated prototype generators. On the other hand, new development methods for the specification of multi-agent systems have been proposed. These methods often commit to a specific agent architecture. For instance, (Kinny, Georgeff and Rao, 1996) describe a language on the one hand based on the BDI agent architecture (Rao and Georegeff, 1991) and on the other hand based on object-oriented design methods. A more in depth comparative analysis of these methods from the perspective of compositionality and the related principles presented in this paper would be interesting further research.

The compositional approach to agent design followed in this paper has some aspects in common with object oriented design methods; e.g., (Booch, 1994; Coleman, Arnold, Bodoff, Dollin, Gilchrist, Hayes, and Jeremaes, 1994; Rumbaugh, Blaha, Pelerlani, Eddy, and Lorensen, 1991). However, there are differences as well. Examples of approaches to object-oriented agent specifications can be found in (Aridor and Lange, 1998; Kendall, Murali Krisna, Pathak, and Suresh, 1998). A first interesting point of discussion is to what the difference is between agents and objects. Some tend to classify agents as different from objects. For example, Jennings and Wooldridge (1998a) compare objects with agents on the dimension of autonomy in the following way:

> 'An object encapsulates some state, and has some control over this state in that it can only be accessed or modified via the methods that the object provides. Agents encapsulate state in just the same way. However, we also think of agents as encapsulating behavior, in addition to state. An object does not encapsulate *behavior*: it has no control over the execution of methods – if an object x invokes a method m on an object y, then y has no control over whether m is executed or not – it just *is*. In this sense, object y is not autonomous, as it has no control over its own actions. In contrast, we think of an agent as having *exactly* this kind of control over what actions it performs. Because of this distinction, we do not think of agents as invoking methods (actions) on agents – rather, we tend to think of them *requesting* actions to be performed. The decision about whether to act upon the request lies with the recipient.'.

Some others consider agents as a specific type of objects that are able to decide by themselves whether or not they execute a method (objects that can say 'no') upon a received message, and that can initiate action (objects that can say 'go') without any message received.

A difference between the compositional design method DESIRE and object-oriented design methods in representation of basic functionality is that within DESIRE declarative,

knowledge-based specification forms are used, whereas method specifications (which usually have a more procedural style of specification) are used in object-oriented design. Another difference is that within DESIRE the composition relation is defined in a more specific manner: the static aspects by information links, and the dynamic aspects by (temporal) task control knowledge, according to a prespecified format. A similarity is the (re)use of generic structures: generic models in DESIRE, and patterns (Alexander, 1977; Gamma, Helm, Johnson, and Vlissides, 1995; Fowler, 1997; Grand, 1998) in object-oriented design methods, although their functionality and compositionality are specified in different manners, as discussed above.

The use of reflection principles to specify the control of complex dynamic reasoning patterns in diagnosis is described in (Treur, 1991). The approach to diagnosis using fine-grained dynamic control of (limited) reasoning by means of dynamic generation of targets in particular is described in (Treur, 1993). Temporal semantics for the dynamics of this reasoning pattern are introduced in (Treur, 1994); see also chapter ** of this book. The generic model for reasoning with and about dynamic assumptions is introduced in (Treur, 1992). Semantics for this approach to reasoning with and about dynamic assumptions (temporal epistemic reflection) are introduced in (Hoek, Meyer and Treur, 1994); see also chapter *** of this book. In (Brazier, Treur and Wijngaards, 1996) and (Brazier, Jonker, Treur and Wijngaards, 1999) more details about these diagnostic reasoning models can be found.

References

Alexander, C. (1977). A Pattern Language. Oxford University Press.

Aridor, Y., and Lange, D.B. (1998). Agent Design Patterns: Elements of Agent Application Design. Proc. of the Second Annual Conference on Autonomous Agents, Agents'98, ACM Press, pp. 108-115.

Barringer, H., M. Fisher, D. Gabbay, R. Owens, and M. Reynolds, (eds.) (1996). The Imperative Future: Principles of Executable Temporal Logics. Research Studies Press, Chichester, United Kingdom, 1996.

Booch, G. (1994). Object-Oriented Analysis and Design (2nd ed.). Addison-Wesley. Reading, MA.

Bradshaw, J. (1997) (e.d). Software Agents. AAAI Pres, 1997.

Brazier, F.M.T., Cornelissen, F., Gustavsson, R., Jonker, C.M., Lindeberg, O., Polak, B., and Treur, J., Agents Negotiating for Load Balancing of Electricity Use. In: M.P. Papazoglou, M. Takizawa, B. Krämer, S. Chanson (eds.), Proceedings of the 18th International Conference on Distributed Computing Systems, ICDCS'98, IEEE Computer Society Press, 1998, pp. 622-629.

Brazier, F.M.T., Dunin-Keplicz, B.M., Jennings, N.R. and Treur, J. (1995). Formal specification of Multi-Agent Systems: a Real-World Case. In: V. Lesser (ed.), Proc. of the First International Conference on Multi-Agent Systems, ICMAS'95, MIT Press,

Cambridge, MA, pp. 25-32. Extended version in: International Journal of Cooperative Information Systems, M. Huhns, M. Singh, (eds.), special issue on Formal Methods in Cooperative Information Systems: Multi-Agent Systems, vol. 6, 1997, pp. 67-94.

Brazier, F.M.T., Jonker, C.M., Jungen, F.J., Treur, J. (1998). Distributed Scheduling to Support a Call Centre: a Co-operative Multi-Agent Approach. In: Proceedings of the Third International Conference on the Application of Intelligent Agents and Multi-Agent Technology (eds. Nwana, H.S. and Ndumu, D.T.), The Practical Application Company, Blackpool, pp. 555-576. Also in: Applied Artificial Intelligence Journal, vol. 13, 1999, pp. 65-90. Special Issue with selected papers from PAAM'98.

Brazier, F.M.T., C.M. Jonker, J. Treur (1996). Modelling Project Coordination in a Multi-Agent Framework. In: Proceedings of the Fifth Workshops on Enabling Technology for Collaborative Enterprises, WET ICE'96, IEEE Computer Society Press, 1996, pp. 148-155.

Brazier, F.M.T., Jonker, C.M., Treur, J. (1997). Formalisation of a cooperation model based on joint intentions. In: (Müller, Wooldridge and Jennings, 1997), pp. 141-155.

Brazier, F.M.T., Jonker, C.M., and Treur, J. (1998). Principles of Compositional Multi-agent System Development. In: J. Cuena (ed.), Proceedings of the 15th IFIP World Computer Congress, WCC'98, Conference on Information Technology and Knowledge Systems, IT&KNOWS'98, 1998, pp. 347-360.

Brazier, F.M.T., Jonker, C.M., Treur, J., and Wijngaards, N.J.E (1999). On the Use of Shared Task Models in Knowledge Acquisition, Strategic User Interaction and Clarification Agents. International Journal of Human-Computer Studies. In press, 1999.

Brazier F.M.T., Treur J., Wijngaards N.J.E. (1996). The acquisition of a shared task model; In: Shadbolt, N., O'Hara, K., and Schreiber, A.Th (eds.), Advances in Knowledge Acquisition, Proc. of the 9th European Knowledge Acquisition, Workshop, EKAW'96, Lecture Notes in Artificial Intelligence, vol. 1076, pp. 278-289.

Chandrasekaran, B. (1986) Generic tasks in knowledge-based reasoning: high-level building blocks for expert system design. IEEE Expert, Vol. 1, pp. 23–30.

Coleman, D., Arnold, P., Bodoff, S., Dollin, C., Gilchrist, H., Hayes, F., and Jeremaes, P. (1994). Object-Oriented Development: the FUSION method. Prentice Hall International: Hempel Hempstead, England.

Fowler, M. (1997). Analysis Patterns: Reusable Object Models. Addison Wesley.

Gamma, E.R., Helm, R., Johnson, R., and Vlissides, J. (1995). Design Patterns: Elements of Reusable Object-Oriented Software. Addison-Wesley.

Grand, M. (1998). Patterns in Java: Volume 1. John Wiley and Sons.

Genesereth, M.R., Fikes, R.E. (1992). Knowledge Interchange Format - version 3 - reference manual. Technical Report Logic Group, Logic-92-1, Stanford University, Stanford, CA.

Herlea, D.E., Jonker, C.M., Treur, J., and Wijngaards, N.J.E. (1999). Specification of Behavioural Requirements within Compositional Multi-Agent System Design. In: F.J. Garijo, M. Boman (eds.), Multi-Agent System Engineering, Proceedings of the 9th European Workshop on Modelling Autonomous Agents in a Multi-Agent World, MAAMAW'99. Lecture Notes in AI, vol. 1647, Springer Verlag, Berlin, pp. 8-27.

Hoek W. van der, Meyer J.-J., Treur J., (1994). Formal semantics of temporal epistemic reflection, In: L. Fribourg and F. Turini (ed.), Logic Program Synthesis andTransformation-Meta-Programming in Logic, Proc. Fourth Int. Workshop on Meta-programming in Logic, META'94, Lecture Notes in Computer Science, vol. 883, Springer Verlag, 1994. pp. 332-352.

Jennings, N.R., and M. Wooldridge (1998a), Applications of Intelligent Agents. In: (Jennings and Wooldridge, 1998b), pp. 3-28.

Jennings, N.R., and M. Wooldridge (eds.) (1998b), Agent Technology: Foundations, Applications, and Markets. Springer Verlag.

Jonker, C.M., Treur, J. (1997). Compositional Verification of Multi-Agent Systems: a Formal Analysis of Pro-activeness and Reactiveness. In: W.P. de Roever, H. Langmaack, A. Pnueli (eds.), *Proceedings of the International Workshop on Compositionality, COMPOS'97*. Lecture Notes in Computer Science, vol. 1536, Springer Verlag, 1998, pp. 350-380

Kendall, E.A., Murali Krisna, P.V., Pathak, C.V., and Suresh, C.B. (1998). Proc. of the Second Annual Conference on Autonomous Agents, Agents'98. ACM press.

Kinny, D., Georgeff, M.P., Rao, A.S. , A Methodology and Technique for Systems of BDI Agents. In: W. van der Velde, J.W. Perram (eds.), Agents Breaking Away, Proc. 7th European Workshop on Modelling Autonomous Agents in a Multi-Agent World, MAAMAW'96, Lecture Notes in AI, vol. 1038, Springer Verlag, 1996, pp. 56-71.

Luck, M., d'Inverno, M.. A formal framework for agency and autonomy. In: V. Lesser (ed.) Proc. of the first International Conference on Multi-Agent Systems, ICMAS'95, pp. 254-260, AAAI Press, 1995.

Müller, J.P., Wooldridge, M.J., and Jennings, N.R. (eds.) (1997). Intelligent Agents III (Proc. of the Third International Workshop on Agent Theories, Architectures and Languages, ATAL'96), Lecture Notes in AI, volume 1193, Springer Verlag, 1997

Nwana, H.S., (1996), Software Agents: an Overview, Knowledge Engineering Review, vol. 11(3), pp. 205 - 244.

Nwana, H.S., and D.T. Ndumu, (1998), A Brief Introduction to Software Agent Technology. In: (Jennings and Wooldridge, 1998b), pp. 29 – 47.

Rao, A.S., Georgeff, M.P., Modeling rational agents within a BDI architecture. In: R. Fikes and E. Sandewall (eds.), Proceedings of the Second Conference on Knowledge Representation and Reasoning, Morgan Kaufman, 1991, pp. 473-484.

Rumbaugh, J., Blaha, M., Pelerlani, W., Eddy, F., and Lorensen, W. (1991). Object-Oriented Modelling and Design. Prentice Hall, Eaglewoods Clifs, NJ.

Treur, J. (1991). On the use of reflection principles in modelling complex reasoning, International Journal of Intelligent Systems, vol. 6 (1991), pp. 277-294.

Treur, J. (1992). Interaction types and chemistry of generic task models. In: Linster, M. and Gaines, B. (eds.). Proc. of the Fifth European Knowledge Acquisition Workshop, EKAW'91. GMD Studien, vol. 211, pp. 390-414

Treur, J. (1993). Heuristic reasoning and relative incompleteness. International Journal of Approximate Reasoning, vol. 8 (1993), pp. 51-87.

Treur J., (1994). Temporal Semantics of Meta-Level Architectures for Dynamic Control of Reasoning. In: L. Fribourg and F. Turini (ed.), Logic Program Synthesis and Transformation-Meta-Programming in Logic, Proceedings of the Fourth International Workshop on Meta-Programming in Logic, META'94. Springer Verlag, Lecture Notes in Computer Science, vol. 883, 1994. pp. 353-376.

Treur J., Willems M. (1994). A logical foundation for verification. In: A.G. Cohn (ed.), Proc. of the 11th European Conference on Artificial Intelligence, ECAI'94. John Wiley & Sons, Chichester, 1994, pp. 745-749.

Wooldridge, M. and Jennings, N.R. (1995a). Agent theories, architectures, and languages: a survey. In: (Wooldridge and Jennings, 1995b), pp. 1-39

Wooldridge, M.J., and Jennings, N.R. (eds.) (1995b). Intelligent Agents (Proc. of the First International Workshop on Agent Theories, Architectures and Languages, ATAL'94), Lecture Notes in Artificial Intelligence, Vol. 890, Springer Verlag, Berlin.

Wooldridge, M.J., and N.R. Jennings (1995c). Intelligent Agents: Theory and practice. In: Knowledge Engineering Review, 10(2), pp. 115-152.