

# A Distributed Decision Support Architecture for the Diagnosis and Treatment of Breast Cancer

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**Abstract.** Clinical decision support for the diagnosis and treatment of breast cancer needs to be provided for a multidisciplinary team to improve the care. The execution of clinical knowledge in an appropriate representation to support decisions, however, is typically centrally orchestrated and inconsistent with the nature and environment that specialists work together. The use of guideline language of *PROforma* for breast cancer has been examined with the issues raised, and an agent-oriented distributed decision support architecture is put forward. The key components of this architecture include a goal-decomposition structure (shaping the architecture), agent planning rules (individual decision-making), and agent argumentation rules (reasoning among decision options). The shift from a centralised decision support solution to a distributed one is illustrated using the breast cancer scenario and this generic approach will be applied to a wider range of clinical problems in future.

**Keywords:** Agent · Breast cancer · Distributed clinical decision support · Goal · Rule

## 1 Introduction and Motivation

Breast cancer remains an important cause of morbidity and mortality around the world. One woman in 9 will develop breast cancer at some time during her lifetime, and breast cancer causes around 13,000 deaths per annum in the UK alone [1]. In improving outcomes in breast cancer, the very first key recommendation given by the Department of Health and the National Institute for Clinical Excellence is that, women should be treated by a multidisciplinary team of healthcare professionals having all the necessary skills [2]. This means a group of specialists will get involved in, and share responsibilities and decisions for a patient's care. It has been found that 65 or more significant decision points will be required across disciplines for the diagnosis and treatment of breast cancer [3]. Therefore, it is important to provide the clinical decision support that can effectively retrieve up-to-date clinical knowledge, match the knowledge against patient data and interpret implication, and assist clinicians to make the best decisions in compliance with the evidence. Representation and execution of clinical knowledge in formal guideline languages towards decision support is a widely recognised approach

but enactment of guidelines today is typically centrally orchestrated. This is inconsistent with real life situations as specialists work in quite ad hoc ways, dynamic in the nature of participation and collaboration, and over a flexible time period and space scope. Hence, a distributed decision support architecture is required to cope the challenges raised by complex diseases such as breast cancer, with the growing specialisation and ever increasing inter-relation in medicine today.

To this end, we work closely with the team from Oxford University where the widely regarded guideline language of *PROforma* has been originally established and engaged in decision support for the past thirty years. A distributed decision support architecture is proposed in this paper to fit today's environment, and it will be based on the agent technology with many advantages in applying to medicine [4].

## 2 The Background of Guideline Languages and *PROforma*

Evidence-Based Medicine promotes conscious and explicit use of best evidence in making clinical decisions [5]. Evidence may be gained from rigorous scientific studies and after evaluation, the strongest evidence will be used to design and develop clinical guidelines that apply to populations: "systematically developed statements to assist practitioners and patient to make decisions about appropriate health care for specific circumstances" [6]. In the UK, the National Institute for Health and Clinical Excellence (NICE) provides national clinical guidelines, e.g. [2, 11] for breast cancer, enabling timely translation of research findings into health and economic benefits. However, compliance with guidelines in practice leaves much to be desired, due to unawareness of such guidelines by clinicians and lack of robust implementation.

For these reasons, clinical guidelines are computerised and formally represented from conventional paper-based format, whereas patient symptoms and signs are matched with guidelines, candidate clinical options can be offered and evaluated, patient-specific advices generated, and direct links provided to the supporting evidence as part of the advices. This will raise the quality of care, as decision-making is in consistency with published and peer-reviewed evidence. Representation of guidelines using formal guideline representation languages is growing, including Arden Syntax [7], Guideline Interchange Format (GLIF) [8], *PROforma* [9, 10] and so on.

*PROforma* is a computer-executable clinical guideline and process representation language, developed at Cancer Research UK. The language provides a small number of generic task classes for composing into clinical task networks: An *Enquiry* is a task for acquiring information from a source (users, local records, remote systems, etc.). A *Decision* is any kind of choice between several options (diagnosis, risk classification, treatment selection, etc.). An *Action* is any kind of operation that will effect some change to the external world (administration of an injection or a prescribing). A *Plan* is a "container" for any number of tasks of any type, including other plans, usually in a specific order. On completion of modelling *PROforma* tasks for a guideline, an application will be enacted by an engine. It has web contents dynamically generated on interface during the execution of tasks, i.e. forms for requesting information, groups of checkboxes or radio-buttons for choosing among decision candidates, and declaration about clinical procedures to be carried out. *PROforma*'s simple task model has proved

to be capable of modelling a range of clinical processes and decisions, and a wide range of applications have been developed over the past thirty years (see [10] for detailed syntax and semantics of the language and [www.openclinical.net](http://www.openclinical.net) for use cases).

### 3 Triple Assessment for Breast Cancer

Triple Assessment is a common procedure in the National Health Service of UK for women suspected with breast cancer and referred to specialised breast units. Patients may be presented by their GPs [11] or following breast screening in the case of women aged between 50 and 70 who are invited for screening mammography every 3 years, through the NHS Breast Screening Programme (NHSBSP) in England [12] or the Breast Test Wales Screening Programme (BTWSP) in Wales. In both situations, it is best practice to carry out, in the breast unit, a “same day” clinic for evaluating the grade and spread of the cancer, if any, or a “triple” assessment:

1. Clinical and genetic risk assessment,
2. Imaging assessment by mammography or ultrasound (which radiological investigations to perform),
3. Pathology assessment by core biopsy, fine needle aspiration, or skin biopsy (which pathological investigations to perform).

An optimum way needs to be selected to manage the patient based on examination, imaging and pathology results [13], and when these are considered together, the diagnostic accuracy can exceed 99 %. If a cancer diagnosis is confirmed, the patient may enter final treatment and management. A major part of the NICE Care Pathway [2] of “Early and locally advanced breast cancer overview” is shown in Fig. 1, where the triple assessment is a central component.

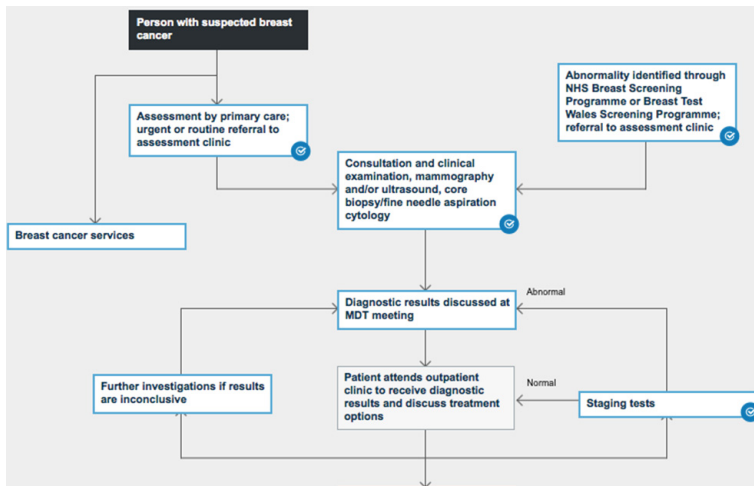


Fig. 1. A partial view of NICE Care Pathway for breast cancer

## 4 The Centralised Solution and Its Problems

The PROforma representation of Triple Assessment guideline is presented in Fig. 2. It can be edited via a toolset, and saved to a single guideline file for central interpretation and execution via an engine.

In the specification, a “top level” plan is defined as a container for all tasks, starting from an *‘examination’*, an Enquiry type of task responsible for gathering relevant clinical examination information and genetic risk assessment. This is followed, when any abnormality is revealed, by a *‘radiology\_decision’*, a Decision type of task that determines which is the right mode of imaging for this patient. Three candidates, “do a mammogram of both breasts”, “do an ultrasound of the affected area” and “do neither” are available for selection. After reasoning and recommendation, and a user confirmation, either a *‘mammography\_enquiry’* or *‘ultrasound\_enquiry’* may run to collect data regarding the imaging test result. The process continues with a *‘biopsy\_decision’*, that determines which is the right mode of biopsy among four candidates of “ultrasound/mammogram/freehand guided core biopsy”, “ultrasound/mammogram/freehand guided fine needle aspiration”, “skin biopsy”, and “no biopsy”. A biopsy method will be selected and later performed, and data regarding the test result collected (on examination of the tissue sent to pathologist). Finally, a *‘management\_decision’* will run and consider all of three test results, referring the patient to other speciality/geneticist, entering the patient to a multidisciplinary meeting with high/low suspicion of cancer for surgery and/or adjuvant therapy, or into a high-risk follow-up protocol.

In this single specification, “Decision” components for distinctive expertises have been intertwined, along with data definition, referencing, and so on. “Enquiry” components for data gathering at various sites have also been mixed up. It will be hard, at the moment, to separate decision logic from other abstractions of data or computation, clarify boundary of clinical participation, or maintain and reuse guideline knowledge. Unless tasks for the decision and alike are distributed across clinical sites for execution, the clinical needs cannot be met in reality.

## 5 The Distributed Solution of an Agent Architecture, an Overview

Being knowledge-driven, goal-oriented, imitative to human minds, and with features of decentralisation and pro-activeness, the computational entities of agents are very suitable for distributed clinical decision support [15]. In this design, agents running in a computing world are representatives of clinicians at dedicated clinical sites. On behalf of their associated clinicians with distinct roles, they are responsible for a series of tasks: receiving clinical events, generating interfaces and presenting what is already known about the subject and what needs to be solved at that point of care, collecting clinical data following consultation, examination, or investigations, and finally suggesting diagnosis or intervention plans out of the alternatives.

```

/** PROforma (plain text) version 1.7.0 */
metadata :: '';
title :: 'triple_assessment'; .....
data :: 'patient_age';
      type :: integer;
      caption :: 'What is the patient's age?';
end data.
data :: 'patient_latestExamination_nippleDischarge';
      type :: text;
      caption :: 'Does the patient have nipple discharge?';
      range :: "no", "yes";
end data.
.....
plan :: 'triple_assessment';
      component :: 'examination';
      component :: 'further_investigation_decision';
            schedule_constraint :: completed('examination');
      component :: 'radiology_decision';
            schedule_constraint :: completed('further_investigation_decision');
      component :: 'ultrasound_enquiry';
            schedule_constraint :: completed('radiology_decision');
      component :: 'mammography_enquiry';
            schedule_constraint :: completed('radiology_decision');
      component :: 'biopsy_decision';
            schedule_constraint :: completed('ultrasound_enquiry');
            schedule_constraint :: completed('mammography_enquiry');
      component :: 'manage_patient_plan';
            schedule_constraint :: completed('biopsy_decision');
      component :: 'discharge_plan';
            schedule_constraint :: completed('further_investigation_decision');
.....
plan :: 'manage_patient_plan';
precondition :: result_off(further_investigation_decision) = manage_patient
or result_off(further_investigation_decision) = do_further_investigations;
      component :: 'treatment_decision';
      component :: 'management_decision';
            schedule_constraint :: completed('treatment_decision');
      component :: 'refer_to_other_speciality';
            schedule_constraint :: completed('management_decision');
      component :: 'corrective_surgery';
            schedule_constraint :: completed('management_decision');
      component :: 'give_drugs_action';
            schedule_constraint :: completed('management_decision');
      component :: 'follow_up';
            schedule_constraint :: completed('management_decision');
      component :: 'inform_gp';
            schedule_constraint :: completed('management_decision');
.....
end plan.
.....
plan :: 'discharge_plan';
precondition :: result_off(further_investigation_decision) = discharge;
      component :: 'reassure_and_discharge';
      component :: 'inform_gp';
end plan.

```

**Fig. 2.** The PROforma specification for Triple Assessment (the “orchestration” mode)

At runtime, collaborative sites will maintain their decision process, logic, and autonomy. Agents will retrieve the decision support knowledge executable to them, and share among themselves investigation results or decision outcomes by message passing. A number of common services such as data referencing, computation, and deduction will also be established. They can facilitate agents across multidisciplinary sites to be able to share the same consistent understanding of knowledge structure at design time, and draw up concrete clinical data and decisions at runtime, but are out of the scope of this paper and not detailed further. Previously, PROforma composes clinical tasks such as enquiries, decisions, and actions into clinical decision processes for breast cancer, under a centralised or “orchestration” execution control. That model is reorganised into a set of interaction among separate agents in a distributed or “choreography” manner, agent tasks being temporally scheduled and activated under sequential or conditional circumstances, as shown in Fig. 3.

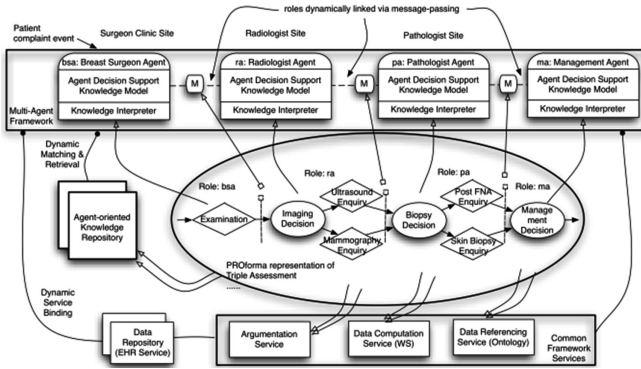
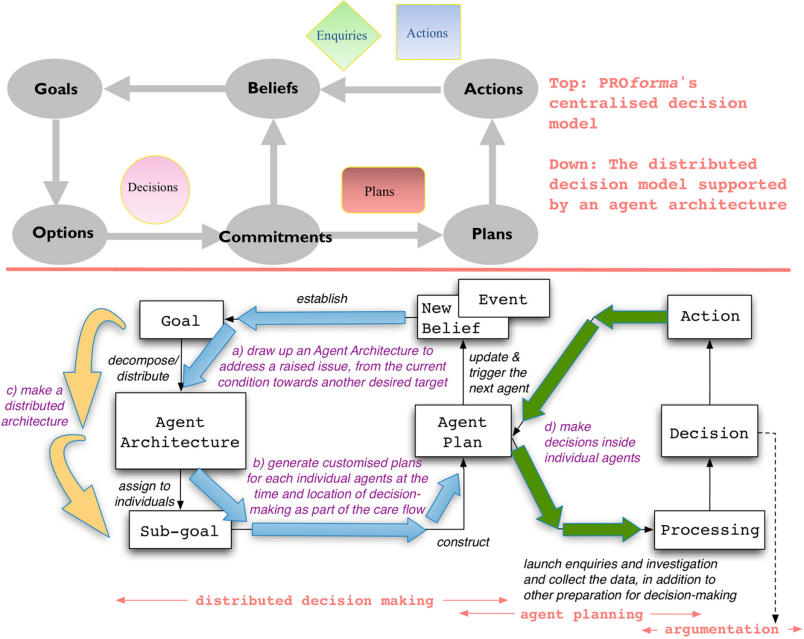


Fig. 3. The distributed architecture for breast cancer (the “choreography” mode)

The most prominent notions that need to be raised in this design may be a *Goal*, being a desired state to which a subject seeks to reach from the current state; an agent *Architecture*, where often a goal cannot be reached directly in one go by the subject alone, instead others may join and this forms an architecture; and a *Plan*, which will be drawn up by an individual agent in executing decision logic, sharing the decision result in the architecture, and coordinate among agents towards their shared goal.

The centralised decision model of PROforma and the distributed agent decision model are shown side by side in Fig. 4. In the upper part, four types of tasks of PROforma as mentioned in Sect. 2 are present. They are used for the composition of task-networks and server the centralised decision model. Here two cognitive state-transition cycles specify how a decision may be made prior to its implied action carried out [9]. Each round of decision-making runs iteratively and separately, with no explicit connection between them. In the lower part, two cycles are present in the distributed model as well, where an agent architecture is made up (cycle in blue) prior to each agent constructing its own plan (cycle in green). The agent architecture is made up in such a way that its corresponding goal reflects what needs to be addressed

(start-up by an event in line a), collectively by multiple agents and which decomposes and assigns tasks to individual agents (end-up in plans in line b). The decomposition of a goal into assignable sub-goals makes the distributed decision architecture (line c), and the construction, processing, and execution of plans makes individual agent decisions (line d). The reference model of distributed decision-making shown in Fig. 4 will be further illustrated of its application to Triple Assessment in the next section as follows: goal-decomposition (Sect. 6.1), agent planning (Sect. 6.2), agent argumentation (Sect. 6.3), and towards implementation (Sect. 6.4).

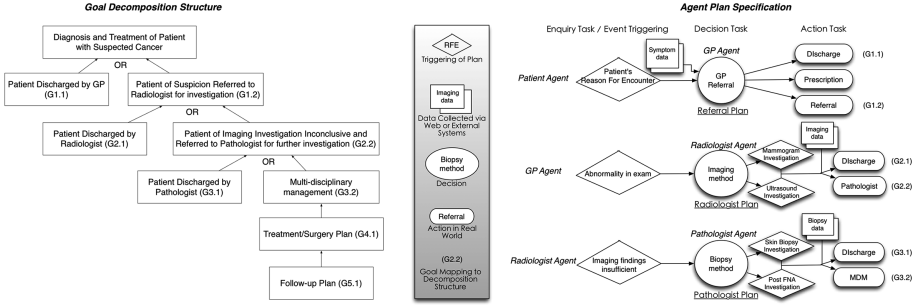


**Fig. 4.** The original centralised decision model and the distributed agent decision model (Color figure online)

## 6 Goal-Decomposition, Agent Planning, and Argumentation

### 6.1 The Goal-Decomposition Structure

The generic process of goal-decomposition for making the distributed decision architecture in Fig. 4 is applied here to the Triple Assessment scenario. A goal-decomposition tree structure is constructed after several decomposition iterations, with its top-level goal as root at top right through atomic sub-goals as leaves at bottom, shown in the left hand side of Fig. 5. Also, the generic process of constructing plans is applied several times and three of which are shown with concrete contents filled up in the right hand side of Fig. 5. A plan is central to an agent in capturing a sequential task workflow and responsible for achieving a sub-goal in a hierarchical goal-decomposition



**Fig. 5.** A goal-decomposition structure (and its matching plans) for breast cancer

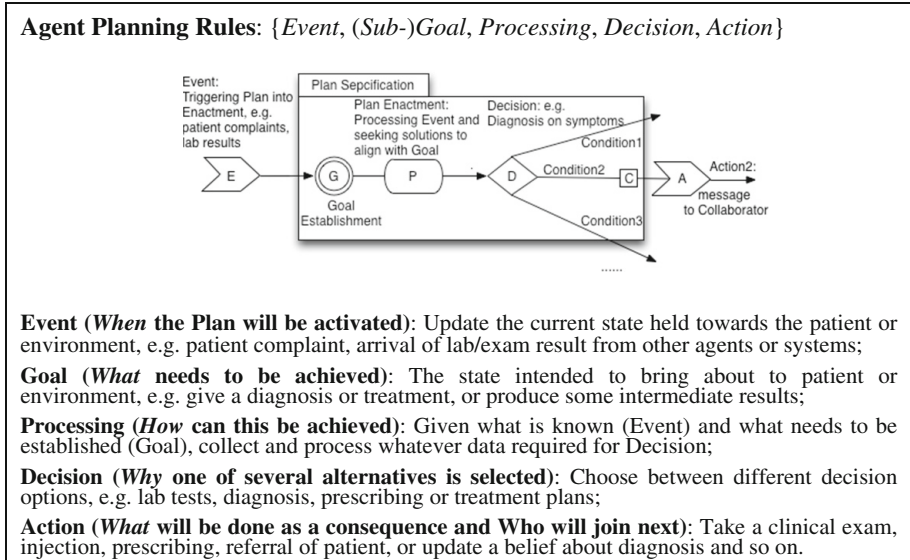
structure and ultimately, a group of collaborative agents will plan together for accomplishing the top-level goal.

In the example, after a patient of suspicion is referred to a radiologist for investigation (sub-goal of G1.2), she may either be discharged (G2.1) or her imaging investigation inconclusive and referred to a pathologist for further investigation (G2.2). Accomplishing G1.2 requires that its lower level sub-goal of either G2.1 or G2.2 is satisfied (and the same holds true to G2.2, G3.2 and so forth). This part of goal structure with distinct tree branches can map to the second plan in the right hand side of Fig. 5, the Radiologist Agent employing an imaging method and deciding whether a patient can be ruled out of breast cancer or not and taking actions correspondingly. The outcome of plan execution or the selection of one goal branch against another not just guides the behaviour or action of this agent alone but also has influence over the agent architecture. As for the radiologist, the goal-decomposition suffices at level three of the tree structure regarding to one decision or level four (or even deeper later) to the other, additional agents may need to participate for the fulfillment of yet incomplete goal in the latter occasion. As opposed to that, arriving at the leaf node of G1.1, G2.1, or G3.1 implies that their upper level (and top-level) goal is achieved (sub-goals turn into actionable tasks) and there is no need of introducing more agents.

## 6.2 The Agent Planning Rules

The very fundamental structure of an Agent Plan in Fig. 5 includes an Event triggering component responsible for cross-site communication, a Decision component, and an Action component with recommended clinical interventions as a result. The Plan structure is compliant with the design principle of clinical decision support that customised clinical plans and actions need to be generated by matching generic guidelines against current patient-specific conditions [14]. The triplet structure can be extended and termed as **Agent Planning Rules** shown in Fig. 6, by making the plan execution context (its Goal) explicit and hiding away the low-level computational details (its Processing) in this abstraction. An agent may maintain high-level decision logic with regard to up-to-date clinical knowledge and meet upcoming needs, as soon as its Planning Rules (re-)configured. This will permit the same agent to use whatever local





**Fig. 6.** The scheme of Agent Planning Rules

resources available to solve different problems in participating different agent teams with different goals, but yet behave in a uniformly structured manner. This can offer us better maintainability, execute-ability, and separation of concerns.

Overall, the aimed agent decision architecture is event-driven and the dynamic matching, interpretation, and execution of **Agent Planning Rules** constitute the behaviour of individuals and the group, as follows:

- (1) On receipt of a clinical **Event** (*When*), an agent matches it against its subscribed Planning Rules to find the appropriate one to deal with this, and populates this generic Planning Rule with specific situation data extracted from the message, which may indicate new patient data, lab or exam results available from another agent, etc.;
- (2) The agent updates its current state about the environment, which causes it to establish a new **Goal** (*What*);
- (3) Taking into account what is already known about the patient and what needs to be established by the Goal, the agent launches enquires about patient symptom, lab investigation and whatever data is missing prior to a decision being concluded and after certain computation and deduction, together structured as a **Processing** (*How*);
- (4) A **Decision** (*Why*) can then be made: among a set of optional decision branches, each having a pre-condition for choosing this branch and an Action as post-condition of committing to it, the optimum one will be recommended with supporting evidence;
- (5) An **Action** (*What*) will be committed eventually, either automatically or with user authorisation. In many cases this includes the passing of a message to the next agent, moving towards collaborative decision-making and progressing along care pathway.

In the example of the Radiologist Agent (its Plan shown in Fig. 5), upon the receipt of an *Event* message on abnormality found in exam, it will set up an imaging investigation to reach a *Goal* of either ruling out the patient with breast cancer, or findings of imaging inconclusive and then the result sent to a pathologist for further investigation. A *Decision* needs to be made on choosing between two screening techniques of mammography and ultrasound, and the result needs to be judged following the chosen screening. This involves *Processing* prior to the judgement and an *Action* of discharge or referral afterwards.

### 6.3 The Agent Argumentation Rules

In Agent Planning Rules, a decision may lead to different actions in different circumstances, thus the selection of a diagnosis, treatment, or care pathway among many choices. **Agent Argumentation Rules** can be linked to this decision structure in order to support reasoning. They represent declarative logic relationship between clinical

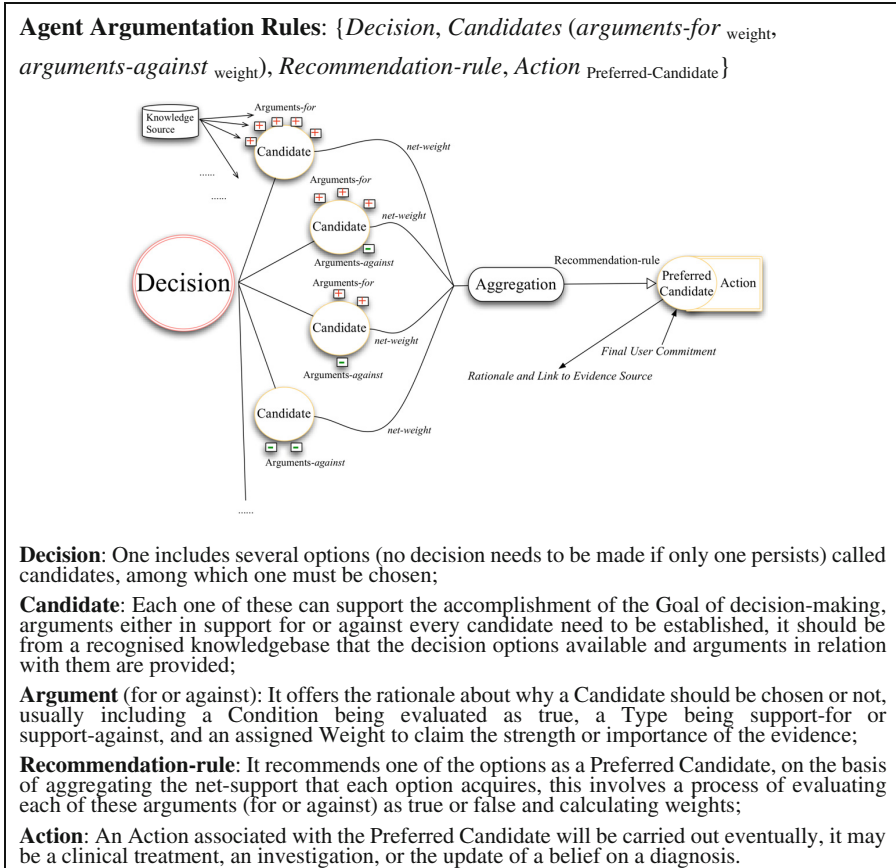


Fig. 7. The scheme of Agent Argumentation Rules

symptoms or other findings as premise, and judgment of arguments in support for or against decision candidates as consequence, shown in Fig. 7.

In the example of Radiologist Agent, a **Decision** needs to be made on the use of an imaging method for investigation, with two **Candidates** available: *Candidate 1* “Do a mammogram of both breasts” and *Candidate 2* “Do an ultrasound of the affected area”. The rational in deciding between them is provided by guidelines and evidence shows that, **Arguments** that support *Candidate 1* include if the patient has been assessed as being at medium or high genetic risk and is over 30 years old, if she has a nipple inversion, axillary lymph node, non-cyclical breast pain, or localised breast nodularity, among others; **Arguments** against *Candidate 1* include if the patient is pregnant, if she is younger than 35 years old, among others. Arguments for or against *Candidate 2* can be established likewise with corresponding weights. A Preferred Candidate will then be provided following a **Recommendation-rule**, as the satisfaction of arguments can be evaluated and the net-support of each candidate calculated and aggregated, not detailed in this paper. An **Action** of discharging the patient or referring her to a pathologist will be carried out as the eventual outcome.

```

G := G0 // the top-level goal
Glist := decompose(G)
while not empty(Glist) do
  get next Gi from Glist
  // find all agents which are able and willing to play the associated role
  Alist := callForParticipation(matchRole(Gi))
  if not empty(Alist) then
    // select a potential agent from the list
    Agenti := select(Alist)
    // find from knowledgebase all the candidates that can satisfy the sub-goal
    Olist := options(satisfy(KB, post-condition(Gi)))
    Oordered-list := argumentation(Olist) // invoke the argumentation and order the options
    Oi := select(Oordered-list) // get the best possible option for now
    Pi := plan(Agenti, Oi)
    // re-plan if the sub-goal cannot be satisfied
    while not succeeded(Pi) do
      execute(Pi)
      Si := belief(Agenti)
      // check if the sub-goal succeeds after executing the chosen plan
      if satisfy(Si, post-condition(Gi)) then
        succeeded(Pi)
        belief(Agenti+1, Si) // share the current patient data and decisions
        pre-condition(Gi+1) := post-condition(Gi) // link the goal states
      else
        Oi := select-next(Oordered-list) // get the next best possible option
        Pi := plan(Agenti, Oi) // re-plan for this agent
      end-if
    end-while
  end-while
end-if
end-while

```

**Fig. 8.** An algorithm for goal-decomposition, agent planning and argumentation

## 6.4 Towards Implementation of the Distributed Agent Decision Architecture

Upon the completion of executing **Agent Argumentation Rule** on two investigation methods and the imaging result judged to be suspicious, relevant data will be sent to a pathologist on patient referral. It completes the **Agent Planning Rule** of this agent and indicates a step further to the goal. Interactive interfaces between agents and their assisting clinicians will be activated at radiologist site and others, and thus support provided for decision-making in the distributed environment as shown in Fig. 3. An algorithm for implementing the overall architecture is shown in Fig. 8.

## 7 Discussion and Conclusions

In this paper, an agent-oriented decision support architecture is put forward to drive distributed decision-making for breast cancer. The work reviews and addresses the issues raised by the centralised approach of *PROforma* and a generic distributed solution is provided: (1) goal-decomposition structure supports the shaping of the agent decision architecture and the elaboration of plans; (2) agent planning rules support individual decision-making with a goal-achieving capability and an agent-executable structure; and (3) agent argumentation rules further support reasoning among decision options and provide a mechanism for recommending a preferred option, being an appropriate diagnostic test, a treatment option, or a particular care pathway. The work builds on top of our previous work [15] and the use of the Triple Assessment of breast cancer scenario illustrates the shift from a centralised decision-making solution to a distributed one. However, the approach is not limited just to this particular problem. Instead, we are working on this generic and versatile approach and applying it to a wider range of clinical guideline knowledgebase across medicine and will make it more powerful for distributed decision support by agents.

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