Agent Decision-Making under Uncertainty: Towards a New E-BDI Agent Architecture Based on Immediate and Expected Emotions

Hanen Lejmi-Riahi, Fahem Kebair, and Lamjed Ben Said

***Abstract*—Over the last decade, emotions have received considerable attention among scholars in agent oriented systems. In fact a large amount of computational models of emotions has been developed and a new generation of artificial agents has emerged to give rise to emotional agents, in particular the Emotional BDI (EBDI) agents. However, in spite of the several interesting studies that have been conducted to underline the role of emotions in decision-making, few works in the agent community have shed the light on the influences of both immediate and expected emotions to drive decision-making. In this context, we intend to propose a new conceptual model of EBDI agency that involves the interplay among immediate emotions, expected emotions and rational decisions of artificial agents.**

***Index Terms*—Belief desire intention architecture, decision-making, emotional agents, expected emotions, immediate emotions.**

I. Introduction

Traditionally, there was a conviction that emotion and rational thought are two separated entities. Emotion has been viewed as disruptive for a rational decision. However, more recent researches in psychology, neurobiology and cognitive science have attempted to highlight the way in which emotion, aside from cognition, is relevant to the decision-making process. For example, according to the work conducted by the neurobiologist Damasio, patients having brain disorders in the part which is responsible for monitoring emotions have difficulties to make decisions [1].

Consistent with these researches findings, new tendency in artificial intelligence and decision theory fields has been established. In particular, early works that elaborate on decision-making in artificial agents tend to develop models of purely rational agents which are based on a decision-theoretic framework. More specifically, the agent decision-making model is designed so as to maximize a certain form of utility function in order to find the best alternative among the different available options [2]. Moreover, another approach to model rational agents has been proposed in order to reflect the human-like reasoning; it is based on three mental states that are Beliefs, Desires and Intentions (BDI) to represent respectively, the information, motivational, and deliberative states of the agent [3]. According to the BDI model, the agent behavior and its decision-making are determined by these mental states (i.e. beliefs, desires and intentions). However, in line with the multi-disciplinary growing interest in emotions and the scientific proof of their usefulness for taking decisions, scholars of artificial agents start to account for emotions when building upon intelligence and realism in rational agents [4]. As a result, a large amount of computational models of emotions were developed and a new generation of artificial agents took the direction over emotional agents, in particular the Emotional BDI (EBDI) agents.

Since the main purpose of our work is to extend previous works on models of EBDI agents' architectures, we aim to take into consideration emotion-related influences on decision-making under uncertainty. Our contribution springs from the idea proposed in [5] by the two authors Loewenstein and Lerner. Their work has been influential in psychology, decision theory and management but not sufficiently in agent-oriented systems researches. It addresses the issue of developing a theoretical framework that serves to explain the way in which emotions influence decision-making. According to the authors, emotions can be either expected or immediate and each one of them has special implications in the decision process. In that, our work aims at proposing a new E-BDI agent architecture based on immediate and expected emotions. By adopting this new approach of modeling, we intend to build artificial agents that end up making better decisions and operate as faithful as possible to the human reasoning pattern.

The remainder of this paper is organized as follow. In the next section, we introduce the theoretical framework of our research work. In the following, we describe previous work on agent-based models that incorporate expected emotions, immediate emotions and their impact on the agent decision-making. After that, we present the proposed EBDI architecture. Finally, we conclude the paper and outline future work.

II. Theoretical Framework

To present our agent architecture, we consider necessary to introduce the theoretical background that underpins our work. To this end, we first describe the adopted framework used to explain the emotional influences on decision-making. Then, we present the EBDI architecture as a reference approach to account for emotions in rational BDI agents.

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A. Emotional Influences on Decision-Making under Uncertainty

Apart from the scientific proof of their functional role in cognitive tasks, emotions have been the subject of interest of many researches that have investigated the way they do influence decisions. An interesting approach to deal with the emotional influences on decision-making, that we intend to adopt in our work, is based on the distinction between expected and immediate emotions. The work conducted by [5] sheds the light on these two types of emotions. In fact, it investigates their determinants as well as their consequences while focusing on their impacts on decision-making as presented in Fig. 1. The authors define the expected emotions as the predictions about the emotional experience if ever the decision option takes place and the associated outcomes occur. As such, this kind of emotions underlines the consequentialist character of decision-making. Almost models of decision-making, such as the expected utility, assume that the expected emotions are the only kind of emotions that impacts the human decision [6]. Theorists, in this field, argue that people select the alternative that maximizes their positive emotions and minimizes the negative ones. However, besides to expected emotions, immediate emotions can considerably impact the decision process. In [5], immediate emotions refer to emotions felt at the time of the decision-making. They arise either due to the anticipations made about the decision outcomes and their emotional consequences or they can simply be experienced in relation to some situational stimuli unrelated to the decision process itself. A farther point related to the presented reference model, depending on their intensity, immediate emotions can alter decisions directly. Moreover, they can also alter them indirectly by impacting the way expectations are made [5].

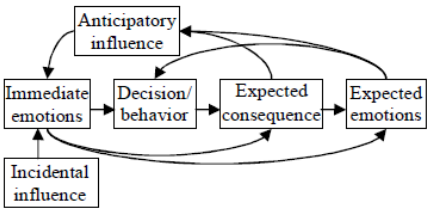

Fig. 1. Determinants and consequences of immediate and expected emotions [5].

B. Emotional BDI Agent Architecture

Although the existence of various approaches to model rational agents, the BDI architecture has been widely accepted by researchers in agent oriented systems. It is considered as a blueprint for autonomous intelligent agents [7]. The significant popularity of this model is due mainly to its foundation on folk psychology that investigates "the way that we think we think" [8, p.6]. As such, it is easier to the agent designer to build on computational human-like decision-making models especially in the context of simulation environments. Agents in the BDI architecture select their behavior on the basis of their mental states (i.e. beliefs, desires and intentions). More specifically, the BDI agents behave along the lines of the human practical reasoning which includes first a process of deliberation followed then by a process of means-end reasoning [9]. While the former aims to produce the agent intentions given the set of its beliefs and its desires (choosing what to do), the latter focuses on the construction of the plans and their execution in order to achieve the agent goals (acting) [7].

More recently, scholars in the agent community started, over the last decade, to pay attention to a new form of BDI agent architecture. Their purpose was to expand the existing works in the BDI agency models and to build on their efficiency and realism. In this context, they have proposed to incorporate artificial emotions next to the classical components of the BDI architecture. Subsequently, several models of emotional BDI agents have been proposed. Among the early attempts, we cite the work of [10] in which the authors have criticized the classical BDI agent architecture and have proposed to extend it with artificial emotions. In fact the agent uses an emotional state manager to control its resources and capabilities and to guide its reasoning process. This way, the emotional agents would be able to cope with uncertainty, complexity and dynamics characterizing the environment in which they operate.

In the same context, another interesting work has been proposed in [11]. It presents a generic architecture for emotional agents called the Emotional BDI (EBDI) in which a particular emphasis is given to the influence of both primary and secondary emotions on the decision-making process. Moreover, by contrast to the conventional BDI architecture, the set of beliefs, in this model, can be supplied not only through perception but also via communication and contemplation. The authors have also proposed to separate the practical reasoning process from the emotional mechanism in order to smooth the injection of an emotional model into the agent reasoning module whenever it is needed.

Recently, Puică and Florea have developed a new architecture for emotional BDI agents [4]. Their work has been inspired by the two aforementioned works of [10] and [11]. In fact, in addition to the set of beliefs, desires and intentions, they have included emotions to the agent architecture. They do reference to [11] to draw on the distinction between primary and secondary emotions in their model. They have also adopted the idea of [10] according to which, when making decisions, resources can be selectively accessed based on emotions.

We believe that the EBDI architecture, as proposed by [4], is the more appropriate for our modeling. In fact, it represents a general domain-independent architecture. Moreover, the practical reasoning (i.e. deliberation and means-end reasoning), as it has been presented, is fully specified with a special emphasis on the influence of emotions on the agents decision-making process.

III. Related Work

In this section we present the work proposed in [6] as an agent-based model that addresses the distinction between expected and immediate emotions and that incorporates their influences on the agent decision-making process (see Fig. 2). According to this model, the immediate emotions are triggered by a direct impact of external or internal stimuli (i.e. physical or physiological changes respectively). The

expected emotions are activated indirectly via perception, choice and appraisal processes. In fact, first, stimuli can be picked up by perception and then, changed into subjective percept. Second, they pass by the choice process which represents the preliminary decision that aims to generate plans that the agent intends to execute given its percepts and a set of other factors. These include the agent goals, beliefs, intentions and knowledge. Third, once sent to the appraisal process, the generated decision and its related expected consequences are evaluated emotionally to activate expected emotions. In addition to emotions activation process, the framework exposes emotions influence on the other components of the model structure. In that, the agent final decision behavior is sketched out according to the choice process as well as the direct impact of both immediate and expected emotions. Moreover, immediate emotions exert an indirect impact on behavior through their influences on perception, choice and expected emotions.

Although this model is similar to ours, as it accounts for both immediate and expected emotions when dealing with the emotional influences on artificial agents' decisions, our model differs in three important ways. First, in spite of its integration into cognitive agent architecture, the decision-making process proposed in [6] does not represent explicitly the mental states of the agents. However, our work is based on the BDI architecture. Accordingly, the interplay between immediate and expected emotions, on the one hand, and the reasoning process components including beliefs, desires and intentions, on the other hand, is well defined. Second, contrarily to their assertion to follow the interaction among expected emotions, immediate emotions and decision as it was presented by [5], the model of Xu and Wang [6] has ignored different components dynamics such as the anticipatory influence of expected emotions on the immediate ones. Third, as it is commonly known, most of the computational models of emotions are based on the appraisal theory according to which emotions are the result of a cognitive evaluation of a situation [12]. Nevertheless, in the aforementioned model, immediate emotions can only be triggered by a direct impact of stimulus. They are then considered as the result of a reactive behavior that doesn't require any deliberation. The authors have used appraisal just to evaluate emotionally the expected outcome of their choices and to generate, accordingly, the expected emotions.

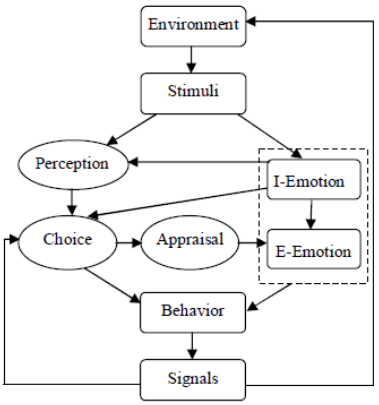

Fig. 2. Emotionally oriented framework of decision-making under risk [6].

IV. Immediate and Expected Emotions in the E-BDI Architectures

Before explaining our proposed architecture, it is necessary to expose the following model assumptions. As it was aforementioned, we are inspired by the work of [4] in order to elaborate on our proposed architecture. In fact, we build upon the EBDI architecture that they have proposed and to which we add the influences of both immediate and expected emotions as described in [5]. We mention also that, in the current paper and for the purposes of simplicity and model comprehensibility, we haven't taken into consideration neither the emotional influences on resources usage nor the personality influences on the agent behavior. Furthermore, in our architecture, we deal only with secondary emotions which require a more complex deliberative process. Thus, we have ignored the primary emotions which are usually associated with reactive behaviors and are typically needed in survival situations [4].

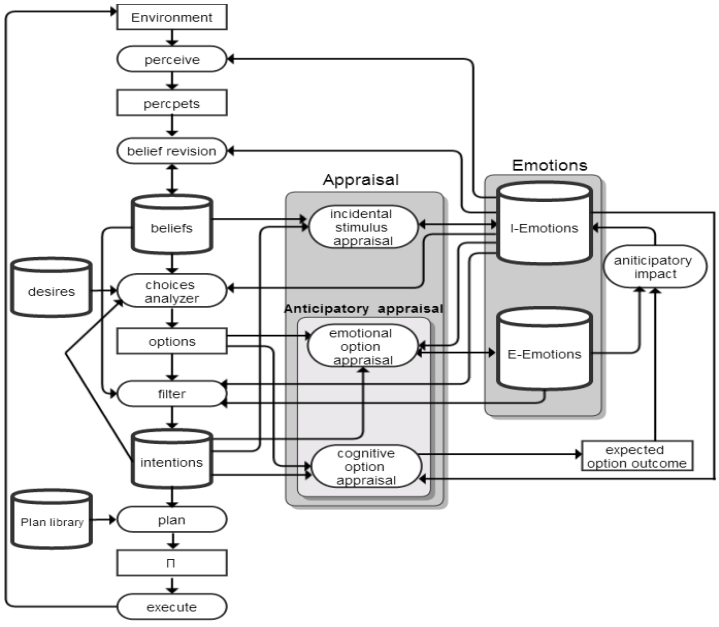

Fig. 3. Proposed EBDI architecture based on expected and immediate emotions.

Our proposed EBDI architecture is schematically presented as shown in Fig. 3. In particular, our contribution, in relation to the work proposed in [4], is emphasized using the dotted outline.

The architecture comprises concepts, functions and interaction mechanisms in relation to the agent practical reasoning (i.e. deliberation and means-end reasoning), its immediate emotions and its expected emotions.

A. Concepts

The proposed EBDI architecture contains the following concepts:

- **Environment (Env)**

It is the part of the world in which the agent operates.

- **Percepts (P)**

They represent information coming from the agent environment.

They are influenced by the agent immediate emotions.

- **Beliefs (B)**

They do refer to the agent mental representation of the states of the world (e.g. its environment, its capabilities, etc.).

They are subjective and they are influenced by immediate emotions.

- **Desires (D)**

They represent the agent desired end-states (i.e. its goals).

They are designed so as to be constant over time as proposed in [4].

- **Options (O)**

They describe the available candidate alternatives that the agent disposes in order to attain its desires.

- **Intentions (I)**

They refer to the agent commitments to perform the selected options.

The commitment of an agent to a particular option can't be interrupted until it is considered either as completely achieved, as unachievable, or as inconsistent with the agent current beliefs.

- **Plan Library (PL)**

It holds the list of plans that the agent uses in order to achieve its desires.

- **Plan ($\amalg$)**

This is the selected sequence of actions that the agent extracts from the plan library in order to achieve its intentions.

- **I-Emotions (IE)**

They represent emotions felt at the time of the decision-making. They arise from a cognitive appraisal of situations (i.e. incidental stimuli). In this context, the OCC model [13] of artificial emotions, which is a computation-oriented and a largely used model in the agent community, can be followed. This emotion-derivation model argues that emotions represent a valence reaction to either the consequence of events, the actions of an agent, or the aspects of objects. This valence reaction is done regarding to the goals, standards, and attitudes of the agent [13].

Immediate emotions can also be influenced by expected emotions and updated following anticipations made about the consequences of a candidate option.

- **E-Emotions (EE)**

They represent predicted emotional experiences of possible outcomes of a chosen option. These emotions are not felt emotions per se. But, they are forecast of possible emotions if ever the decision option takes place and the associated outcomes occur.

Expected emotions are influenced by immediate emotions via an anticipatory appraisal of the candidate option.

Their implementation can be based on a quantitative decision-theoretic framework (e.g. the subjective expected utility or prospect theory) such as in [14]. It can also be built upon a case-based reasoning like in [15].

- **Expected Option Outcome (EOO)**

They describe an anticipated evaluation of a candidate option.

They exercise an anticipatory impact on the immediate emotions.

B. Functions

The set of the architecture concepts are generated, maintained, revised and connected through a set of functions.

We provide below the list of these functions as well as their formalization:

- **Perceive (perceive)**

It captures the input stimuli from the environment.

It is influenced by immediate emotions and aims at generating percepts.

$$perceive: Env \times IE \rightarrow P$$

- **Belief revision function (brf)**

It revises the agent's beliefs on the basis of its percepts, current beliefs and immediate emotions.

$$brf: P \times B \times IE \rightarrow B$$

- **Choices analyzer (chAnalyzer)**

This function represents the first step of the deliberation process.

It aims at generating candidate decision options given the current agent beliefs, desires and intentions.

It is influenced by immediate emotions.

$$chAnalyzer: B \times D \times I \times IE \rightarrow O$$

- **Filter (filter)**

It represents the second step of the deliberation process after the choices analysis.

The purpose of this function is to choose the appropriate options to commit to. It generates intentions according to the candidate options and the set of beliefs.

It is influenced by both immediate and expected emotions.

$$filter: O \times B \times IE \times EE \rightarrow I$$

- **Plan (plan)**

It represents the means-end reasoning.

Depending on the current intentions and the plan library, the agent uses the Plan function to find out the appropriate plan of actions to execute.

$$plan: I \times PL \rightarrow \amalg$$

- **Execute (execute)**

It aims at executing the sequence of actions as defined in the plan specification.

$$execute: \Pi \rightarrow Env$$

- **Incidental stimulus appraisal (isa)**

The purpose of this function is to update immediate emotions given the set of beliefs and intentions. The internal mechanism of this function is based on the cognitive appraisal theory and it uses the OCC emotion-derivation computational model [13] to trigger new immediate emotions.

$$isa: B \times I \rightarrow IE$$

- **Emotional option appraisal (eoa) and cognitive option appraisal (coa)**

These two functions use the decision candidate option, perform respectively an emotional and a cognitive anticipatory appraisal over it and generate the expected emotions (for the *eoa*) and the expected option outcome (for the *coa*).

The *eoa* function uses, in addition, the previous expected emotions to generate the new ones.

The two functions are influenced by intentions and immediate emotions.

$$eoa: O \times I \times IE \times EE \rightarrow EE$$

$$coa: O \times I \times IE \rightarrow EOO$$

- **Anticipatory impact (ai)**

This function deals with the anticipatory influences which are exercised by both the expected emotions and the expected option outcomes and which can fluctuate the immediate emotional states.

$$ai: EOO \times EE \rightarrow IE$$

- **Inconsistent (inconsistent)**

This function verifies if the current intentions are inconsistent with the new incoming beliefs.

It does not appear in the schematic representation of the EBDI architecture. However, it will be discussed in the interaction mechanism described in the following subsection.

$$inconsistent: I \times B \rightarrow \{true, false\}$$

- **Sound (sound)**

This function checks if the plan is still in harmony with the intentions and the new set of beliefs.

It will also be discussed in the following subsection.

$$sound: \Pi \times I \times B \rightarrow \{true, false\}$$

C. Interaction Mechanism of the Architecture Components

This section intends to provide the sequence of the execution process, in a control loop mode, within our proposed agent architecture. It explains the information flow and the interaction mechanisms among the different components. We present also a pseudo-code based description of this process (see Fig. 4).

```
1. //Initialization
2. B ← B0
3. D ← D0
4. I ← I0
5. IE ← IE0
6. EE ← EE0
7. PL ← PL0
8. //Process beginning
9. while true do
10.     P ← perceive(Env , IE)
11.     B ← brf(P , B , IE)
12.     IE ← isa(B , I , IE)
13.     O ← chAnalyzer(B , D , I , IE)
14.     EE ← eoa(O , I , IE , EE)
15.     EOO ← coa(O , I , IE)
16.     IE ← ai(EE , EOO)
17.     I ← filter(B , O , IE , EE)
18.     Π ← plan(I , PL)
19.     while not (empty(Π) or succeeded(I , B)
20.                 or impossible(I , B)) do
21.         a ← head(Π)
22.         execute(a)
23.         P ← perceive(Env , IE)
24.         B ← brf(P , B , IE)
25.         IE ← isa(B , I , IE)
26.         if inconsistent(I , B) then
27.             O ← chAnalyzer(B , D , I , IE)
28.             EE ← eoa(O , I , IE , EE)
29.             EOO ← coa(O , I , IE)
30.             IE ← ai(EE , EOO)
31.             I ← filter(O , B , IE , EE)
32.         end if
33.         if not sound(Π , I , B)) then
34.             Π ← plan(I , PL)
35.         end if
36.     end while
37. end while
```

Fig. 4. Pseudo-code based description of the model execution process.

The execution process is described as follows:

1) When the perception component detects a new stimulus from the environment, it generates new percepts which can be altered by immediate emotions. (Line 10)
2) Beliefs are revised according to the new percepts and the pre-existing current beliefs. Moreover, they can be influenced by the immediate emotions. (Line 11)
3) Due to the cognitive appraisal process, new beliefs, under the influence of intentions, are evaluated and immediate emotions are generated. (Line 12)
4) The agent starts the deliberation process by analyzing its desires, the available information about the environment and its current intentions to generate candidate options. This process is influenced by immediate emotions. (Line 13)
5) From the candidate options and under the influence of immediate emotions and intentions, the agent performs both emotional and cognitive anticipatory appraisals of the options in order to generate respectively new expected emotions and expected option outcomes. (Lines 14 and 15)
6) The anticipatory appraisal may alter the current immediate emotions via the expected emotions and the expected option outcomes. (Line 16)
7) On the basis of the candidate options and the current beliefs, the agent selects the appropriate option with the influence of both immediate and expected emotions. As such, the agent is committed to the selected option which presents its new intentions. (Line 17)
8) After deliberation, the agent is oriented towards finding the appropriate plan of actions (line 18) and executing it. This yields to the intentions achievement. However, while executing the plan sequence of actions, the agent must be aware about its environment. Accordingly, new beliefs are obtained and new immediate emotions can also be triggered (lines 23, 24 and 25). Moreover, basing

on the open-minded agency approach, the agent recognizes the eventual inconsistency of its intentions with the new coming beliefs [4]. Thus, a dropping attitude is adopted focusing on new options, new expectations (emotional and cognitive) and new intentions to produce (lines from 26 until 32). Furthermore, the plan can be revised if it doesn't fit the intentions and the set of beliefs.

We mention that this pseudo-code based description of the model execution process is similar to the one proposed in [4] except the following points that underline our contribution. These include:

1) the distinction between expected and immediate emotions,
2) the expected emotions generation (lines 14 and 28),
3) the appraisal of the expected outcome related to the candidate option (lines 15 and 29),
4) the anticipatory impact of expectations on immediate emotions (lines 16 and 30) and
5) the influence of the expected emotions on options filtering and intentions generation (lines 17 and 31).

V. Conclusion

In this paper, the major expected outcome was to create an enhanced agent model that can be used to simulate the naturalistic human decision-making process as faithful as possible to the real world environment. Accordingly, we developed a new EBDI agent architecture in which the influence of both immediate and expected emotions on the agent decision-making process is incorporated. We were inspired by the decision researches point of view via the work proposed in [5] and also, by the EBDI agents' community findings through the work presented in [4] in order to build upon a new agent model. However, further work remains to be carried out. In that, our work presents a conceptual architecture that needs to be illustrated by a comprehensive scenario example that serves to explain the agent decision-making process and its emotional dynamics. Moreover, more details about the model computational formalization must be discussed. For example, we explain the manner according to which we can combine the BDI logic with quantitative methods of the decision theory in order to model expected emotions. Finally, we need to implement and to test our proposed architecture within a working agent-based simulation system in order to present the experimental results and to validate our approach.

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