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Simulation Model to Estimate Emotions in Collaborative Networks

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Abstract: In recent years, the research on collaborative networks has been pointing to the need to put more emphasis on the social interactions of its participants, along with technical features, as a potential direction to finding solutions to prevent failures and potential conflicts. In this context, a modelling framework called Collaborative EMOtion modelling framework (C-EMO), conceived for appraising the collaborative network emotions that might be present in a collaborative networked environment, is presented, and an implementation approach, based on system dynamics and agent-based simulation modelling techniques, for estimating both the collaborative network emotional state and each member's emotions, is described. The work is divided in two parts: the first considers the design of the models and the second comprises the transformation of these conceptual models into a computer model, providing the proposed simulation model. In order to validate the simulation model, and taking into consideration the novelty of the research area, experiments are undertaken in different scenarios representing several aspects of a collaborative environment and a sensitivity analysis and discussion of the results is performed.

Keywords: collaborative network emotion; collaborative networks; socio-technical complexity; system dynamics; agent-based modelling

1. Introduction

Recent research in Collaborative Networks (CN) has focused on the socio-technical aspects of collaboration, aiming to find solutions to prevent collaboration failures and potential conflicts. According to [1], large complex systems, such as CNs, fail because they do not recognize the social and organizational complexity of the environment in which these systems are deployed. Thus, improvements concerning the social interactions among the players, rather than only the technological aspects of such environments, need to be addressed [2–4].

In this context, a framework for appraising emotions in a CN environment is proposed—the Collaborative EMOtion (C-EMO) modeling framework—which brings a richer perspective to decision-making processes, management of conflicts and failures of collaborative networks [5,6]. C-EMO is aimed at improving the performance of existing CNs by adopting some of the models developed in human and computational sciences. As is known, members of a CN are organizations that might be dispersed geographically with different purposes and competences, and not humans, yet they are managed and operated by humans. Emotions are unquestionably related to humans, involving feelings, experience, behaviour, physiology and cognition, and it is evident that organizations cannot feel emotions in the same way humans do. Nevertheless, a kind of emotional state can be appraised when an organization belongs to a virtual environment that presupposes interaction and collaboration among its members. In the same line of thought, the emotional state of each participating organization would contribute to the assessment of the aggregated emotional state of the CN and, in this way, contribute to its success.

This work is guided by the following research question: "What could be an adequate modeling methodology approach to instantiate the C-EMO modeling framework and which methodologies would be suitable for the estimation/appraisal of collaborative network emotions?". Regarding this, the work presented in this article proposes two simulation approaches for materializing the C-EMO modeling framework: the system dynamics and agent-based techniques.

The remainder of this article is organized as follows: Section 2 presents an overview of the C-EMO framework; Section 3 briefly introduces the system dynamics and agent-based simulation modeling methodologies; Section 4 describes the proposed system dynamics simulation models to appraise the individual member and aggregated network emotions, and the agent-based simulation model to represent the CN environment; Section 5 presents the implementation aspects; Section 6 is dedicated to the validation aspects of the proposed models and, finally, Section 7 concludes and identifies future work directions.

2. C-EMO Modelling Framework

The Collaborative EMOtion modelling framework (C-EMO) [6], represents a system that appraises emotions of members of a collaborative network and reasons about the way emotions affect those members and the entire CN environment. The definition of CN adopted in this research work is: "*A Collaborative Network is a network consisting of a variety of entities (e.g., organizations, people, even intelligent machines) that are largely autonomous, geographically distributed, and heterogeneous in terms of their operating environment, culture, social capital and goals, but which decide to collaborate to better achieve common or compatible goals (e.g., problem solving, production, or innovation), and whose interactions are supported by computer networks*" [7].

In this way, C-EMO systematizes the notion of emotions in the CN context, building on theories of human emotion found in psychology and sociology and formalizing those theoretical models in computational models of collaborative network emotion. C-EMO is built as generically as possible, covering the different typologies of CNs, and serves as a starting point for further implementations and experiments in this area of research. Therefore, it comprises two essential building blocks, as presented in Figure 1: *(i) Individual Member Emotion (IME) Model*, for appraising the emotion of each CN member individually and examining the effects this emotion has on both the CN member's behavior and the CN environment; and *(ii) Aggregated Network Emotion (ANE) Model*, for estimating the overall emotion present in the CN and examining the effects such emotion has on the network environment and its members.

C-EMO considers three distinct types of emotion:

1. *CNE (collaborative network emotion)* which is the "emotion" that represents the collaborative network participants' "feelings" and comprises the types of emotion that are "felt" by individual members and by the CN as a whole;
2. *IME (individual member emotion)* which is defined as the emotion that is "felt" by each CN member as a result of its expectations of the CN, the dynamics of its interactions and collaboration, and the influence of the aggregated network emotion; and
3. *ANE (aggregated network emotion)* which is defined as the emotion that is "felt" by the collaborative network as a whole and that results from the influence of the CN member's individual emotions and the dynamics of the network.

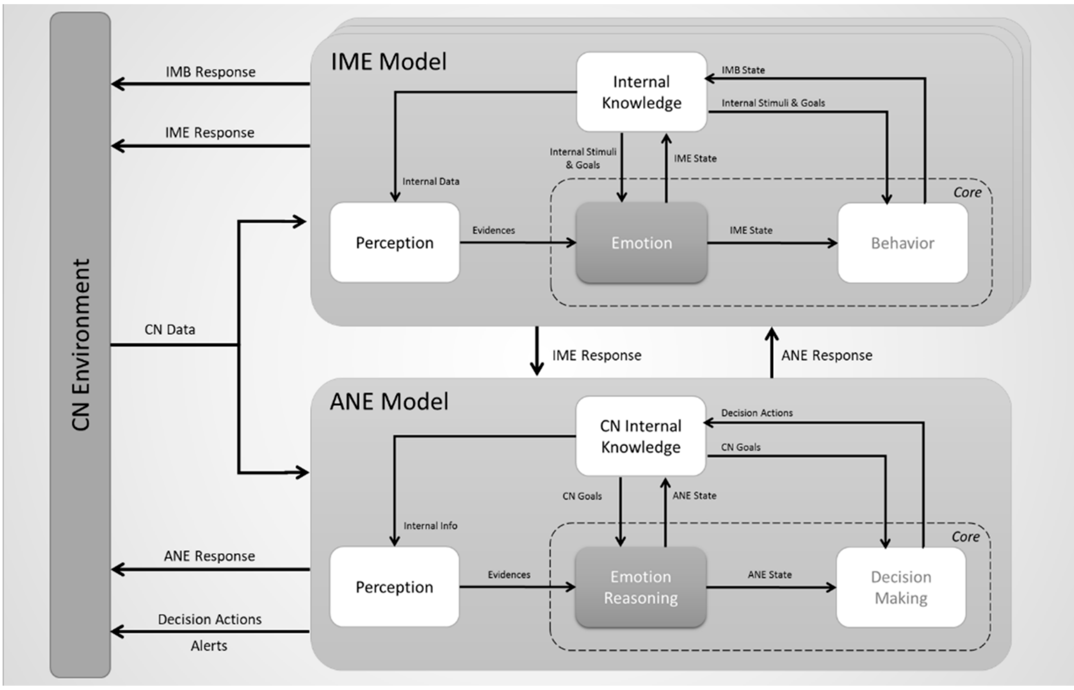

Figure 1. C-EMO: Collaborative EMOtion modelling framework. CN: Collaborative Networks. ANE: Aggregated Network Emotion. IME: Individual Member Emotion IMB: Individual Member Behavior.

The theories that support C-EMO are adapted from the theories of human emotion [6] and consist of a combination of dimensional and appraisal theories. The former is based on Russell's circumplex model of emotion [8], which provides a suitable framework for representing emotions from a structural perspective, defining emotions as states that can be represented on a common multidimensional space and differentiated on the basis of dimensional parameters. In this context, the model that represents the CNE comprises two dimensions: the *Valence*, which represents the pleasure–displeasure continuum, and the *Arousal,* which represents the level of activation, novelty and expectation of the emotional stimuli. Hence, CNEs can be differentiated according to their positive or negative valence and high or low arousal. The emotions that were adopted to describe the "emotional states" within the collaborative environment (with the assumption that they are the more appropriate ones for characterizing emotions, both for the CN and the involved member organizations) are excitement, contentment, frustration, and depression. Accordingly, *excitement* is defined by positive valence and high arousal; *contentment* by positive valence and low arousal; *frustration* by negative valence and high arousal; and finally, *depression* by negative valence and low arousal. Table 1 summarizes the CNEs' dimensional placement.

Table 1. The adopted collaborative network emotion (CNE) emotional states and their dimensional placement.

CNEs	Synonyms	Dimensions
Excitement	Active, enthusiastic, thrilled, electrified	Valence >0; Arousal >0
Contentment	Comfortable, relaxed, satisfied	Valence >0; Arousal <0
Frustration	Afraid, nervous, angry, unsatisfied	Valence <0; Arousal >0
Depression	Hopeless, miserable, uninterested	Valence <0; Arousal <0

The other theory used in C-EMO adopts Scherer's components of emotion [9], which considers emotion as a process rather than as a simply affective state that influences cognition. In this line, four components of CNE are considered: (1) *cognitive or appraisal* component, (2) *feeling* component, (3) *motivational* component and (4) *expression* component. Both the IME and the ANE models' building blocks comprise the four CNEs (for further details, the reader is invited to read [10]).

3. System Dynamics and Agent-Based Modeling and Simulation Techniques

Recent advances in simulation methodologies and the emergent software tools have made simulation one of the most used techniques for complex systems analysis [11–16]. Its application in the CN complex system context is adequate, due to the capacity that simulation has regarding modeling with a suitable degree of realism and attaining accurate system descriptions [17]. This section presents a brief overview of the system dynamics (SD) and the agent-based (AB) modeling and simulation techniques.

3.1. System Dynamics

Initially proposed by Jay Forrester [18], SD is a simulation modeling approach that comprises a methodology and a set of modelling tools that allow understanding of the behavior of complex systems over time. It deals with internal feedback loops and time delays that affect the behavior of the entire complex system and is composed of two primary components: the causal loop diagrams and the stocks and flows diagrams. Causal loop diagramming describes a system in terms of the causal relationships among its components. It is used to represent the basic cause–effect mechanisms of the system and the circular chains of those mechanisms that form a feedback or closed loop. *Stock and flow* diagrams, on the other hand, not only show the relationships between variables that have the potential to change over time (like causal loop diagrams) but also distinguishes between the different types of variables quantifying them.

SD has been applied in many fields, such as in climate monitoring, economic forecasting, predicting social trends like technology adoption or market saturation, and predicting changes in population versus urban sprawl. [19–24]. In general, SD is well accepted by experts in those areas, and the results well established and flexible for many complex systems. In addition, these models show high predictive results of real system behavior. Another pointed advantage is their capacity to be easily explained and intuitive to understand. This is important when it is necessary to discuss complex systems behavior with experts and non-experts. Both diagrams (causal loop and stock and flow) have a high explanatory value for the system they model, and are computable, with a good mathematical foundation, which means that they are quite simple to translate to computer programs. Nonetheless, there are also some disadvantages of using the SD modeling simulation approach. According to [25], one of the limitations of SD is the impossibility of modeling a detailed representation of real-life problems at the entity level, due to the macroscopic nature of and high level of abstraction in this modeling approach. For instance, Brailsford and Hilton [26] stated that SD is less capable of modeling detailed resource allocation problems and optimizations or direct prediction. For further insight on the advantages and disadvantages of SD, the reader can see [27].

3.2. Agent-Based

Agent-Based Modeling and Simulation (ABMS) is another paradigm for analyzing complex systems which has become widespread over the last 20 years. Generally, agent-based models are suitable for complex systems with heterogeneous, autonomous, and pro-active actors, where individuality and changeability cannot be ignored [28–32]. In ABMS, a system is modelled as a collection of autonomous decision-making entities called *agents* (either individual or collective entities such as organizations or groups). Each agent individually evaluates its situation and makes decisions based on a set of rules. Moreover, ABMS provides a useful approach for understanding collective phenomena by studying the rules of the agents involved. In addition to agent state and behavioral logic modeling techniques, visual state charts can also be useful for monitoring agent status during a simulation process, and quickly checking the underlying dynamics of complex models as the simulation evolves over time. Visual interactive modeling approaches, such the ones present in the AnyLogic multi-method simulation tool (The AnyLogic Company, Oakbrook Terrace, IL, USA) [33], include such capabilities when constructing ABMS [34].

Some of the ABMS application areas can be found in cases of vehicles and pedestrians in traffic situations, actors in financial markets, consumer behavior, humans and machines on battlefields, people in crowds, animals and/or plants in eco-systems, and artificial creatures in computer games, among others [29]. More recent research has been conducted on completely new topics, such as modeling the nuclear fuel cycle [35], national culture and innovation diffusion [36], consensus analysis [37], subway station evacuation [38] and passenger terminal safety [39]. More examples can be found in [40].

3.3. Modeling and Simulation Tools

Several modeling and simulation tools are available on the market. Some are for free use; others are proprietary toolkits for commercial use. Examples of such tools can be found in [41–43].

Within recent decades, several software tools have been developed and applied by SD and AB modelers. SD tools have reached a greater stage of maturity than those for AB-based modeling, but still offer many areas for growth. A summary of some simulation tools that feature either SD and AB paradigms, as well as hybrid SD–AB modeling, is given in Table 2.

Table 2. Some of the available modeling and simulation tools for system dynamics (SD) and agent-based (AB)

Tool	SD	AB	Characteristics
Vensim (www.vensim.com)	X		Free version
Repast Simphony (Repast S) (https://repast.github.io/)		X	Dedicated AB prototyping environment Large-scale (scalable) agent development environment Free version
NetLogo (https://ccl.northwestern.edu/netlogo/)		X	Dedicated AB prototyping environment Modified version of the Logo programming language Free
Swarm (http://www.swarm.org/)		X	Large-scale (scalable) agent development environment. Java interface Free
AnyLogic (www.anylogic.com)	X	X	Multi-method tool Integration and interaction of the two methods Large-scale (scalable) agent development environment Java Proprietary toolkit (free version for students)
Insight Maker (www.insightmaker.com)	X	X	Online software Free
MASON (https: //cs.gmu.edu/~{}eclab/projects/mason/)		X	Large-scale (scalable) agent development environment Java Free
Stella/iThink (https://www.iseesystems.com/store/products/ithink.aspx)	X		Multi-method tool (depending on the products) Proprietary toolkit
PowerSim (www.powersim.com)	X		Build models with the System Dynamics approach Run what-if scenarios and do policy design Quickly assemble a flexible user interface Connect to MS Excel or different Databases Free
NOVA (www.novamodeler.com)	X	X	Multi-method tool Java-based modeling platform Free version

The choice of the appropriate tool to satisfy a certain problem is not easy, due to the inherent complexity of systems. In this work, the selection criteria was first based on tools that provide a hybrid SD–AB approach, second on the license character, with a preference for free licenses, and finally on the modeling tool experience of the authors. In this line, the adopted tool is the AnyLogic tool that will be further described in Section 5.

4. Simulation Modeling for CN Emotion Appraisal

The approach proposed in this research work, considers the system dynamics (SD) and the agent-based (AB) techniques as potential solutions for the modelling and simulation of the C-EMO framework. Therefore, the system dynamics modeling approach is proposed as a potential solution for the *Emotion* and *Emotion Reasoning* modules of the IME and ANE model building framework (see Figure 1), while the agent-based model is used to reproduce the CN environment with a focus on the individual member's emotional influence on the overall emotional health of the CN and vice-versa.

In addition, it should be noticed that this approach should not be seen as "the" solution for the modeling and implementation of the C-EMO framework. Many others can be envisaged. It should also be considered that the developed work assumes that a CN for profit is being modeled and that its implemented CN management system is compliant with the ones developed within the context of the ECOLEAD and GloNet EU projects [44–46].

4.1. IMEA SD Model

The ***emotion*** element is one of the core components of the IME model, which, in turn, is composed of three other components: the *Cognitive Appraisal*, the *Activation*, and the *Expression Selection*, as illustrated in Figure 2.

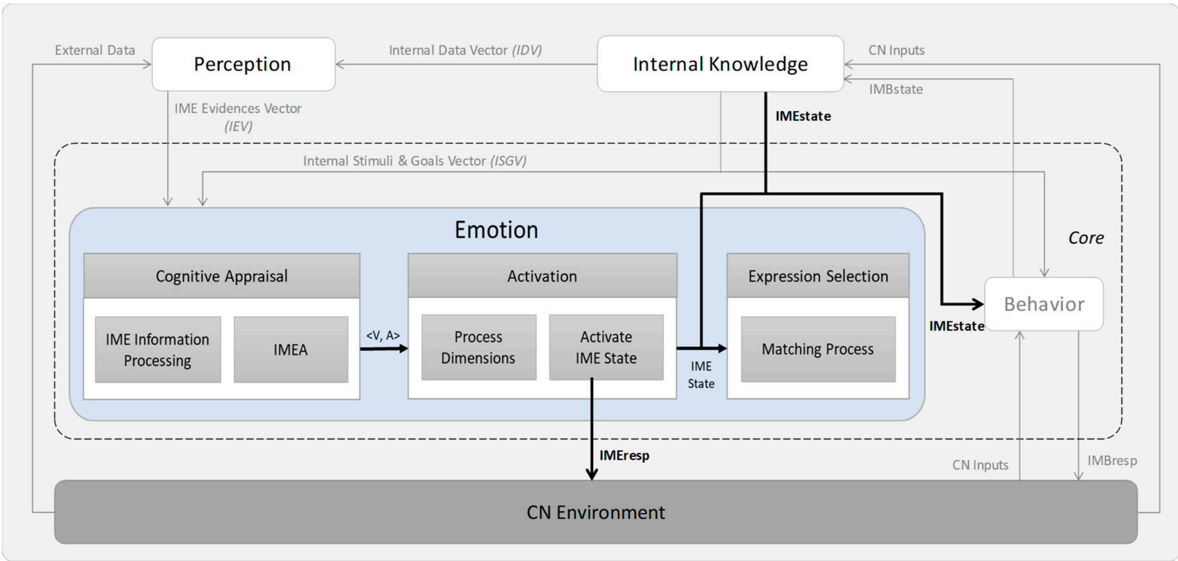

Figure 2. Overview of the individual member emotion appraisal (IME) model composition, with a focus on the emotion element.

Within the cognitive appraisal component, the individual member emotion appraisal (IMEA) element is responsible for calculating the value of the CNE dimensions <Valence, Arousal> or <V, A>. It is the modeling development of this element that is proposed to be designed using the SD methodology: the *IMEA SD Model*.

Therefore, the IMEA SD models the dynamics of the variables that affect the pair <V, A>, which are given by the evidences that are collected and processed by the perception module, and their relationship with the variables that represent the goals and motivations of the individual member. In this context, the IMEA SD model conceptualization consists of *(i)* defining the relevant variables, mapping relationships between these variables; (ii) determining the important causal loop feedback structures; and *(iii)* generating dynamic models as proposed solutions to the problem.

4.1.1. Definition of Variables

According to the C-EMO framework, the variables of the IMEA component are the ones that are provided by the *evidences* and *internal stimuli and goals* input vectors, as shown in Figure 2. The adopted definition of the evidences vector variables for the IMEA SD model is included in Table 3, below.

Table 3. Definition of the variables of the IME evidences vector for the IMEA SD model.

Evidences	Definition
Valence	The latest value of valence, so it represents the initial value of valence before the new estimation.
Arousal	The latest value of arousal, so it represents the initial value of arousal before the new estimation.
Valence Decay	The value of the decay that the valence dimension of IME assumes for the CN member.
Arousal Decay	The value of the decay that the arousal dimension of IME assumes for the CN member.
Virtual Organization (VO) Participation as Planner	The number of times a CN member takes the initiative to prepare a new business to the CN.
VO Participation as Partner	The number of times the CN member is selected to form part of a VO.
Performance Evaluation	The assessment of the performance of the member, according to a set of performance indicators.
Needs and Expectations Met	The value regarding the level of needs and expectations that were accomplished or met in what concerns the member involvement in the CN.
Income from CN	The total earnings of a CN member resulting from its participation in VOs inside the CN environment.
Income Other	The total earnings of a CN member resulting from its participation in external activities to the CN.
Costs and Expenses	The amount of costs and expenses a CN member had independently of being inside the CN or outside.
Belonging Informal Networks	The ratio of the number of informal networks the CN member belongs to, in relation to the total active informal networks within the CN environment.
Shared Knowledge wnd Resources Ratio	The ratio of the total amount of knowledge and resources a CN member shared in relation to the total knowledge and resources present within the CN environment.
Communication Frequency	The rate at which the CN member communicates with others within the CN environment. This variable reflects a result of a social network analysis over the CN environment.
Communication Effectiveness	The rate of understandability of the CN environment about the messages sent by the member. Reflects a result of a social network analysis over the CN environment.
Total CN Members	The total number of registered members in the CN.
Total CN VOs	The total number of VOs operating within the CN environment.
ANE State	The last known value of the ANE state.
CN Trust	The value of the trust assessment results that is conducted to all members.
CN Value System Alignment	The measure of the alignment of the core value system of the CN with the core value systems of all CN members.
Invitation to form VOs	The occurrence of the event "invitation to form VO". The event is triggered when the CN member receives an invitation from the VO planner to join the VO.

Table 3. *Cont.*

Evidences	Definition
Incentive Reward	The occurrence of the event "selected to earn an incentive reward". Event triggered when the member earns a reward after being recognized or after achieving a set of goals of the CN incentive program.
CN Trust Breach	The occurrence of the event "lack of trust situation". The event is triggered whenever the CN trust level achieves the danger threshold.
CN Value System Misalignment	The occurrence of the event "no CN value system alignment". The event is triggered when the result of the assessment of the alignment of the value systems of the CN and the members achieves the misalignment threshold.
CN Social Protocols Violation	The occurrence of the event "social protocols violated". Event triggered when the interactions among a group of CN members become not acceptable according to the established set of social protocols.

The internal stimuli and goals variables are those that represent the inner beliefs, desires and intentions of the member towards its involvement in the CN. Examples could be (i) Beliefs—positive impact of the CN on the external market; potential growth; (ii) Desires—profit; reputation; satisfaction/expectations met; and (iii) Intention—high participation in VOs; high collaboration interaction with peers. In this context, the variables that are proposed are based on these three aspects and are shown in Table 4.

Table 4. Definition of the variables that represent the IME goals and stimuli for the IMEA SD model.

Goals and Internal Stimuli	Definition
Member Satisfaction	The degree of satisfaction of the CN Member. Represents the level of approval when comparing the CN member situation with its expectations and needs.
Profitability	The efficiency measurement of the CN member. This differs from profit. Profit has a currency unit to measure while profitability is generally measured as a ratio of profit to revenue.
Profit	The financial benefit that is realized when the amount of revenue gained from the member business activity exceeds the expenses and costs needed to sustain the activity.
Reputation and Recognition	The potential of recognition and reputation of the CN member by the CN community, i.e., by all CN members. It combines quality of collaboration and competences recognition.
Participation in VOs	The level of participation in Vos, in relation to the total VOs operating in the CN environment.
Collaboration Dynamics	The dynamism of the CN member within the CN environment. This variable is the reflection of the interactions and communication with the other CN members, and the level of willingness to engage with the CN environment.
Commitment	The level of attachment, linkage and enthusiasm a member has with the CN environment. Reflects the connection, the contentment, the involvement and the effort a member puts in the CN.
Trust Level	The level of trust felt by the CN member for the CN environment.
Value System Alignment	The CN member's level of values alignment with the CN environment. Represents the need of the member to be lined up with the organizational values/vision of the CN environment.
Member Motivation	The degree of motivation of the CN member. Represents the member's goal to keep motivated. The motivation is influenced by the member's performance evaluation, satisfaction and incentive rewards and also by the ANE state of the CN environment.

Table 4. *Cont.*

Goals and Internal Stimuli	Definition
Potential Conflicts Creation	The level of creation of potential conflicts by the CN member. Might be activated by a lack of felt trust, by the recognition of values system incompatibility and by the emotional state of the CN member. Avoidance of conflicts is one of the member's expectations.
Communication	The level of communication a CN member has within the CN environment. Represents the relationship between the communication effectiveness, the communication frequency and the level of arousal of the member.

The initial values of these goals and internal stimuli variables are initially equal to zero, then calculated dynamically, taking into consideration the influences of the evidences' input variables on these variables, as will be further explained in the following sections.

4.1.2. Causal Loop Diagram

The IMEA SD causal loop diagram is depicted in Figure 3. Positive linkages are presented with a "+" sign while negative linkages are presented with a "-" sign. As the overall objective is to calculate the two IME dimensions, the valence and arousal variables are in bold, to highlight them.

The main causal loops identified for the IMEA causal model are: commitment reinforcing loop (COMMIT-R); *COLLAB-R* (Collaboration reinforcing loop); capability reinforcing loop (CAPAB-R); communication reinforcing loop (COMMU-R); fulfilment reinforcing loop (FULF-R); valence reinforcement loop (VALE-R); and arousal balancing loop (AROU-B).

A detailed description of each identified causal loop is presented below in Table 5.

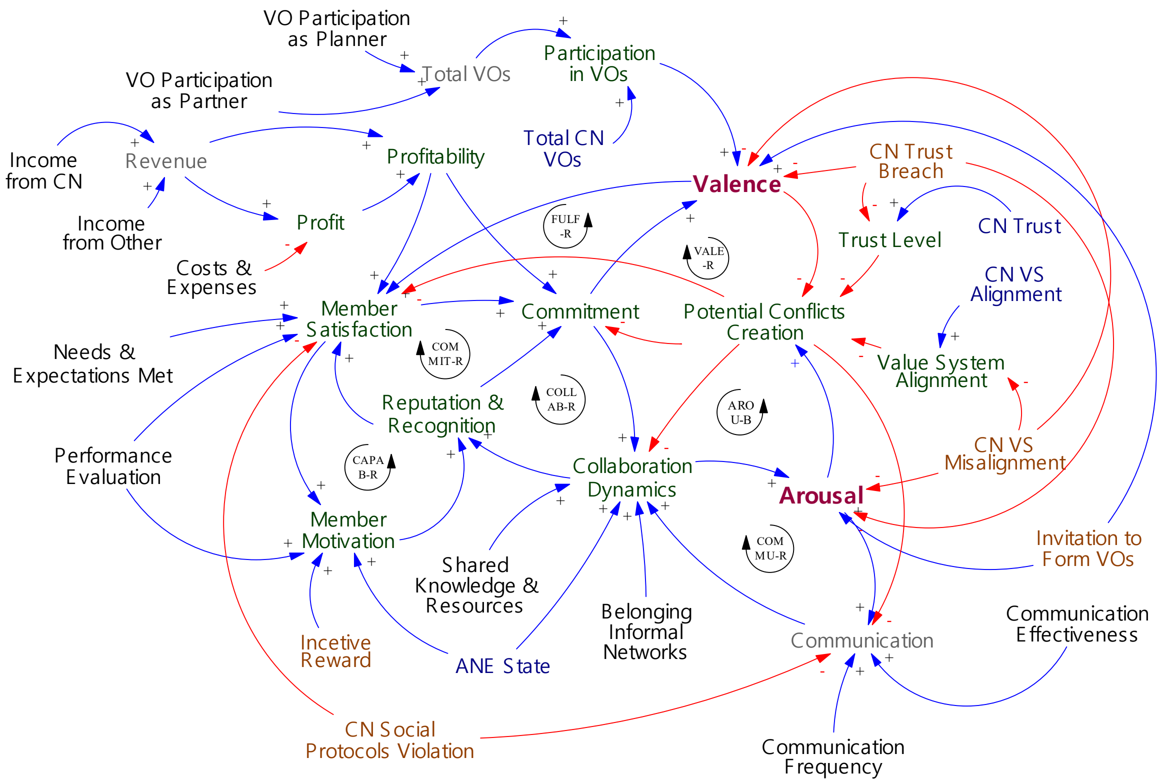

Figure 3. IMEA SD causal loop diagram.

Table 5. Description of each IMEA model causal loop.

Commitment Reinforcing Loop (COMMIT-R)	This reinforcing loop models the dynamics of commitment, collaboration dynamics, reputation and member satisfaction. As collaboration dynamics increase (decrease), the potential for reputation and recognition of the member increases (decreases). This in turn results in the increase (decrease) of members' satisfaction. The increase (decrease) of members' satisfaction positively (negatively) influences the level of commitment of the CN member. This results in an increase (decrease) in motivation to collaborate within the CN environment.
Collaboration Reinforcing Loop (COLLAB-R)	This reinforcing loop models the dynamics of collaboration, reputation and recognition, and commitment. As the potential to be recognized increases (decreases), the member feels more (less) committed to the CN environment. This in turn results in a strengthening (weakening) in motivation to collaborate within the CN environment. When member collaboration increases (decreases), the potential to be recognized and gain reputation also increases (decreases).
Capability Reinforcing Loop (CAPAB-R)	This reinforcing loop models the dynamics of reputation and recognition, member satisfaction, and member performance motivation. When the potential of a good reputation and recognition by the CN peers increases (decreases), it contributes to the growth (decay) of the member's satisfaction (in terms of self-esteem). As soon as the member's satisfaction increases (decreases), the motivation to achieve high levels of performance is incremented (decremented). A high (low) level of performance motivation concedes an increase (decrease) in the potential to be recognized and earn a reputation.
Communication Reinforcing Loop (COMMU-R)	This reinforcing loop models the dynamics of the collaboration dynamics the arousal, and communication. As the collaboration dynamics increase (decreases) arousal is positively (negatively) influenced. As the arousal represents the activation level of the CN member, when it increases (decreases), communication also tends to increase (decrease), because the member has energy to socialize. The effect of this increment (decrement) in communication implies an increase (decrease) in the collaboration forms to put the communication in practice.
Fulfilment Reinforcing Loop (FULF-R)	This reinforcing loop models the dynamics among the member's satisfaction, commitment, and valence. When the member's satisfaction grows (decays), it positively (negatively) influences the level of commitment of the member. In other words, the more (less) satisfied the member, the more (less) committed the member is to its relationship with the CN environment. With the augmentation (diminishing) of commitment, the member increases (decreases) its valence. As valence represents the member's pleasantness–unpleasantness mood, when it increases (decreases), level of satisfaction also increases (decreases) in proportion.
Valence Reinforcement Loop (VALE-R)	This reinforcement loop models the dynamics of the member commitment, the valence, and the potential to create conflicts. As the level of commitment of the CN member fortifies (weakens), valence is positively (negatively) influenced. As valence reveals whether the member is pleased or not, when it increases (decreases) the probability of the member initiating a conflict situation decreases (increases) in the same direction. As the potential to create conflict situations increases (decreases), the level of commitment of the member decreases (increases) accordingly.
Arousal Balancing Loop (AROU-B)	This balancing loop models the dynamics of the potential to create conflicts, the collaboration dynamics, and the arousal. As the potential to initiate a conflict situation increases (decreases), the collaboration dynamics are negatively (positively) affected. A decrease (increase) in the effort to maintain a healthy dynamism in collaboration leads to a drop (rise) in the arousal level. When the level of arousal decreases (increases), it might influence the creation of a conflict situation, depending on the value of valence. In other words, as arousal represents the CN member's level of activity and excitement, when matched with valence it might provoke the creation of a conflict. For instance, if the arousal is negative and the valence is negative, the IME is depression. Depression is associated with inactiveness, which might leave the member quiet, without any energy. Consequently, the probability for creating conflicts is reduced.

4.1.3. Stocks and Flows Diagram

This modeling phase consists of setting up a complete formal model with equations, parameters and initial conditions that represent the IMEA system. The IMEA SD causal loop diagram is used to start this modelling process in order to capture the mental models. Although a causal loop diagram shows the relationships among variables that have the potential to change over time, it does not make the distinction between different types of variables. The stocks and flows diagram allows such distinctions and maintains the causal relationships of the variables. Therefore, stocks and flows, along with feedback, are the two core concepts of systems dynamics theory.

In this context, the IMEA SD stocks and flows diagram is presented in Figure 4. This diagram is based on the IMEA SD causal loop diagram of Figure 3. Thereby, the IMEA SD stocks and flows diagram is a more detailed graphic representation, where the quantification of what was modeled with the causal loop diagram is performed. Besides the output state variables *Valence* and *Arousal*, five other state variables are identified—*MembSatisf*, *Commitment*, *Communication*, *PotenConflictsCreat* and *CollabDynam*. In this way, there are seven structures of stocks-and-flows in the IMEA SD stocks and flows diagram.

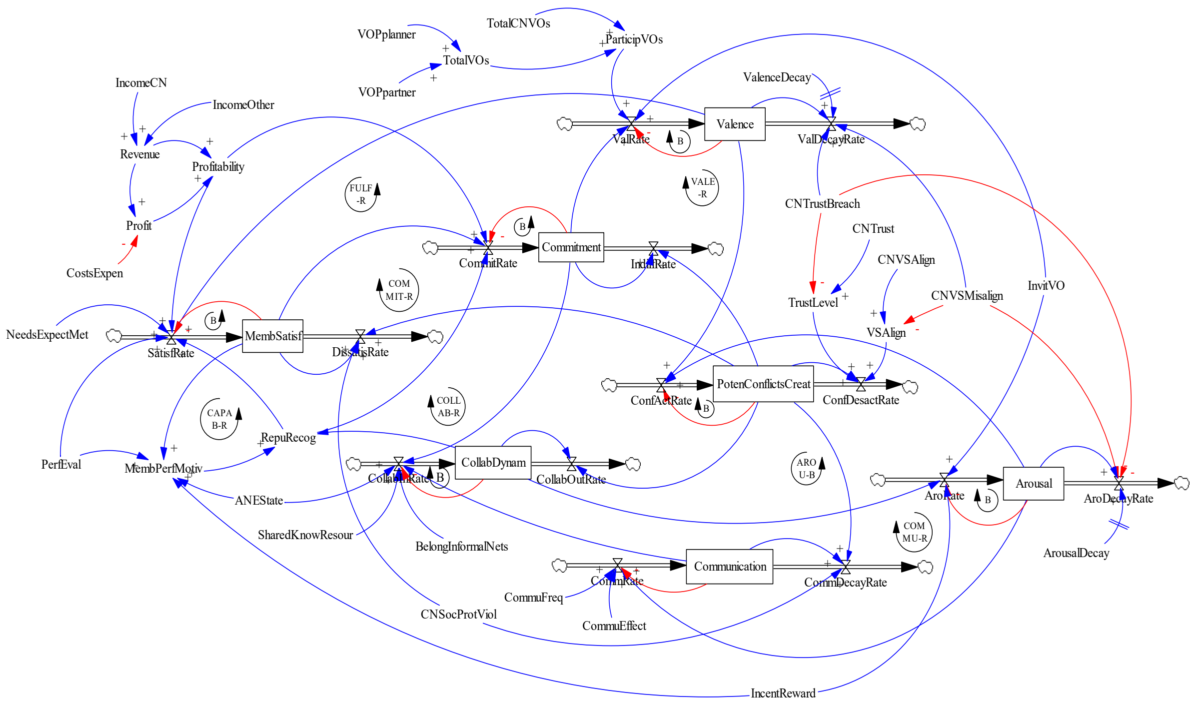

Figure 4. IMEA SD stocks and flows diagram.

These seven structures are modeled with the quantification of its structures. This quantification is formalized with a set of equations that should not be interpreted as the only solution for the IMEA SD modeling approach, but rather as an example of how it could be realized. Furthermore, the values of the given weights will also depend on the requirements and objectives of each CN environment to be modeled, and must be calibrated accordingly. An example of a structural quantification—the *MembSatisf*—is presented below.

Stock and Flow Structure of Member Satisfaction

The *MembSatisf* (member's satisfaction) stock is fed by the *SatisfRate* (satisfaction rate) inflow and is drained out by the *DissatisRate* (dissatisfaction rate) outflow, as illustrated in Figure 5.

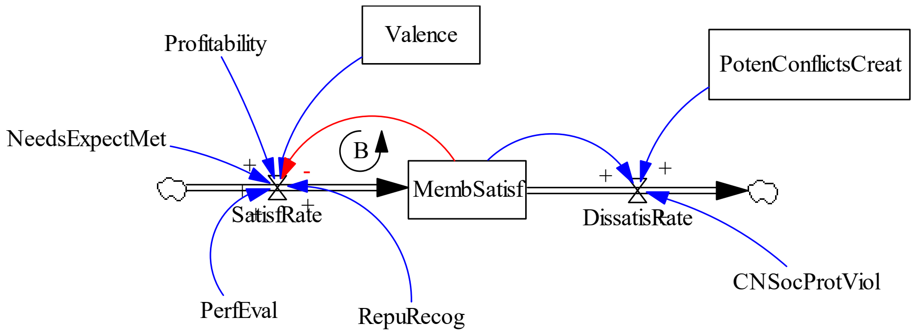

Figure 5. Stock and flow structure of member's satisfaction.

The *MembSatisf* stock variable is then the integral of the difference of *SatisfRate* and *DissatisRate* added to the initial value of the stock, and is represented in Equation (1):

$$\begin{aligned} MembSatisf(t) &= MembSatisf(0) \\ &+ \int [SatisfRate(t) - DissatisRate(t)]dt \\ \text{where,} \quad MembSatisf \in & \ \Re \ \wedge \ \{0 \le MembSatisf \le 1\} \end{aligned} \tag{1}$$

The *SatisfRate* inflow is considered to be primarily driven by the needs and expectations met (*NeedsExpectMet*) and the performance evaluation (*PerfEval*) values at time *t*. Therefore, due to their importance, both parameters should have a multiplicative factor of *wi* that is supposed to be superior in relation to the other involved parameters. The other parameters are *Profitability*, *RepuRecog* (reputation and recognition) and the *Valence* values at time *t*, and have as a multiplicative factor the weight *wj*.

Taking into consideration that Valence varies between −1 and 1, and all the other variables between 0 and 1, it needs to be adjusted accordingly. The adopted criterion was to reference the Valence parameter between 0 and 1. Therefore, a linear function (of the form $y = mx + c$) was fitted in order to reference the range of values. The analytical expression that captures this adjustment is described in Equation (2):

$$ValAdj(t) = 0.5 \times Valence(t) + 0.5 \tag{2}$$

Equation (3), represents the *SatisfRate* inflow.

$$\begin{aligned} SatisfRate(t) = \quad & [w_i \times (NeedsExpectMet \\ & + PerfEval) + w_j \times (ValAdj(t) \\ & + Profitability \\ & + RepuRecog)] / (2 \times w_i + 3 \times w_j) \\ & - MembSatisf(t) \\ \text{where,} \quad SatisfRate, w_i, w_j \quad & \in \ \Re \ \wedge \ w_i > w_j \end{aligned} \tag{3}$$

The *DissatisRate* outflow is considered to be primarily driven by the occurrence of the CN social protocol violation event (*CNSocProtViol*), and secondly by the potential conflicts creation (*PotenConflictCreat*) accumulation. Thus, whenever a *CNSocProtViol* event is triggered, the *DissatisRate* diminishes with a multiplicative factor, *wi*, the total accumulated member's satisfaction (*MembSatisf*). The higher (lower) the *PotenConflictCreat* is, the more (less) the *MembSatisf* diminishes, with an order of magnitude of *wj*. The overall equation to describe the relationship is shown in Equation (4):

$$\begin{aligned} DissatisRate\ (t) & \\ & = MembSatisf(t) \\ & \times (w_i \times CNSocProtViol \\ & + w_j \times ConfPoten(t)) / (w_i + w_j) \\ \text{where,} \quad \{DissatisRate, \quad & w_i, w_j \in \ \Re \ \wedge \ w_i > w_j\} \end{aligned} \tag{4}$$

For the specific case of this IMEA SD model, the values of the weights of this structure quantification and the other six are not the focus, instead, the proof that this modeling framework and simulation approaches are promising for this work's hypotheses.

4.2. ANEA SD Model

The ***emotion reasoning*** element is one of the core components of the ANE model, which comprises three other components as well: the *Reasoning*, the *Activation*, and the *Expression Selection*, as illustrated in Figure 6.

It is the aggregated network emotion appraisal (ANEA) element of the reasoning component that is in charge of estimating the values of the <V, A> dimensions; in the same vein as the previous one, a system dynamics modeling approach is designed for this element—the ANEA SD Model.

In this context, the ANEA SD models the dynamics of the variables that influence the tuple <V, A>, which are given by the evidences that are delivered by the perception module and their relationship with the variables that represent the goals of the CN, as depicted in Figure 6. In this sense, the ANEA SD model conceptualization consists of defining the relevant variables, mapping relationships between the variables, determining the important causal loop feedback structures and generating dynamic models as a solution to the problem.

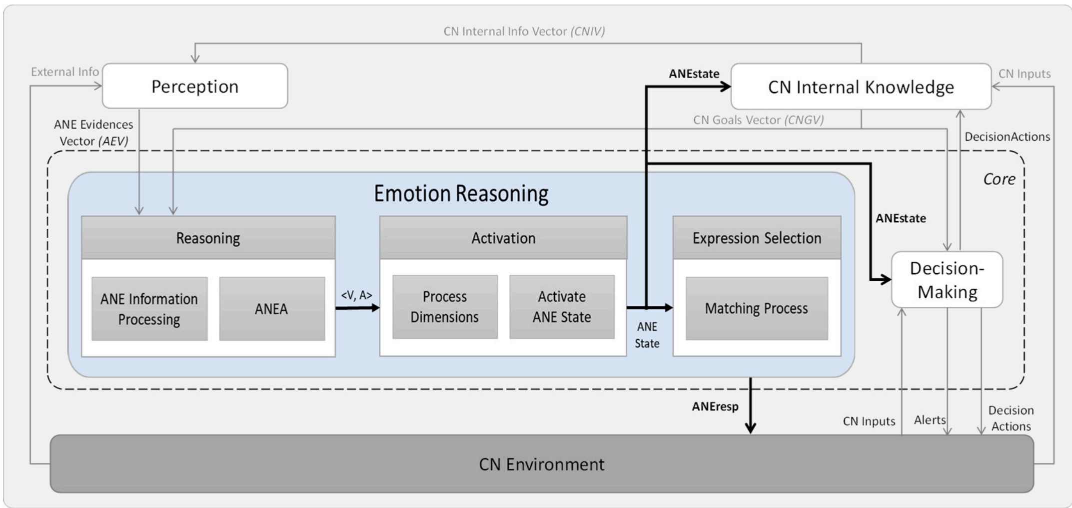

Figure 6. Overview of the ANE Model composition, with a focus on the emotion reasoning element.

The ANEA SD model, like the IMEA SD model, is built on the concept of CNE. In addition, some inspiration also comes from the social, psychological and sociological theories, like the social-constructivist perspective of the social nature of emotions from Averill [47]. According to Averill's theory, emotion derives from the social context, because it is in this social context that emotions have function and meaning. Furthermore, some inspiration from the sustainability mechanisms are also considered in what concerns the goals of the CN. These goals are aligned with the three pillars of sustainability (economic, social and environment), aiming at keeping the CN emotionally equilibrated.

In the case of this ANEA SD model, it is assumed that the ANE state (seen as the social context) influences the individual emotional states (IMEs) of the CN members, with their IME states also responsible, in part, for the overall emotion felt within the CN (the ANE) and, consequently, the CN sustainability.

4.2.1. Definition of Variables

According to C-EMO, the variables of the ANEA component are the ones provided by the ANE evidences vector and by the CN goals vector. The adopted definition of each type of variable in the ANE evidences vector for the ANEA SD model is given in Table 6, below.

Table 6. Definition of the variables of the ANE evidences vector for the ANEA SD model.

Evidences Variables	Definition
Valence	The latest value of the estimated valence, so it represents the initial value of valence before the new estimation.
Arousal	The latest value of the estimated arousal, so it represents the initial value of arousal before the new estimation.
Valence Decay	The value of the decay that the valence dimension of ANE assumes for the CN environment.
Arousal Decay	The value of the decay that the arousal dimension of ANE assumes for the CN environment.
Total CN Members	The total number of registered members in the CN.
Active Members	The number of the active members within the CN.
Total CN VOs	Total number of VOs of the CN environment. Includes the VOs that successfully finished, the VOs that are under operation, the VOs that are in the formation phase and the ones that failed.
VOs Successfully Finished	Total number of VOs that have successfully finished within the CN environment.
VOs Under Operation	Total number of VOs that are in the phase of operation within the CN environment.
VOs Failed	Total number of VOs that have failed either in the creation or the operation phase within the CN environment.
VOs Being Created	Total number of VOs that are in the phase of creation within the CN environment.
CN Performance Evaluation	The performance evaluation value of the CN. Represents the assessment of the performance of the CN according to a set of performance indicators.
CN Trust	The level of trust that is established among the members involved in the CN environment according to a pre-defined set of trust criteria. Represents the value of the trust assessment of all CN members.
CN Value System Alignment	The measure of the alignment of the value system of the CN with the value systems of all CN members.
CN Sharing Ratio	The ratio of knowledge and resources sharing within the CN. Results from the (sum of shares per CN members divided by the total CN shares) divided by (the total CN members).
CN Informal Networks Ratio	The ratio of informal networks within the CN per CN member. Results from (the sum of informal networks that a member belongs to divided by the total amount of informal networks) divided by the (total CN members).
Communication Intensity	The measure of the overall frequency of interactions amongst members of the CN. Represents the dynamics of communication within the CN.
CN Income	The total earnings of the CN resulting, for instance, both from the members' fees and the pre-established percentage of the VOs' overheads.
CN Costs and Expenses	The total costs and expenses of the CN. Costs and expenses represent the amount that must be paid in order to get something, such as specific software or the expenses of insurance and taxes.

Table 6. *Cont.*

Evidences Variables	Definition
Excitement Frequency	The total amount of excitement present amongst the CN members. It is the total number of members that forms the excitement IME state within the universe of the CN.
Contentment Frequency	The total amount of contentment present amongst the CN members. It is the total number of members that forms the contentment IME state within the universe of the CN.
Frustration Frequency	The total amount of frustration present amongst the CN members. It is the total number of members that forms the frustration IME state within the universe of the CN.
Depression Frequency	The total amount of depression present amongst the CN members. It is the total number of members that forms the depression IME state within the universe of the CN.
Neutral Frequency	The total amount of neutral IME present amongst the CN members. It is the total number of members that forms the neutral IME state within the universe of the CN.

The CN goals variables that are assumed for the ANEA SD model are those that represent the inner aspirations of the CN in order to be successful and sustainable.

According to Camarinha-Matos, Afsarmanesh [48], the areas of Collaborative Networks (CN) and Sustainability are creating synergies that bring benefits for both scientific domains. These synergies are leading to novel areas of application, like the collaborative agribusiness ecosystems [49] or the collaborative networks and ageing [50,51]. Furthermore, mechanisms inspired in the biological ecosystems, like the business ecosystems, have demonstrated that some models, systems and processes may mimic nature in order to apply them to human situations. These mechanisms are being studied in the emerging discipline of biomimicry or biomimetics [48,52].

According to Adams [53], sustainability is divided into three pillars: economic, social, and environmental/ecological. Taking into consideration the biomimetic nature of this work, the identified CN goals lay out the knowledge and mechanisms that lead to sustainable and successful collaboration environments. Hence, the proposed CN goals are compliant with the three pillars of sustainability, leading to the core goal of this work that relies on collaborative network emotional health and wellbeing. Table 7 defines the variables that represent the CN goals.

Table 7. Definition of the variables that represent the CN goals.

CN Goals	Definition	Sust. Pillars
Collective Performance	The collective contribution to the performance of the CN. Reflects the dynamics of the organizational, business and social practices, relating the results of the CN to the intended goals and objectives.	Economic Social
Financial Health	The financial health or monetary situation of the CN. It measures the overall financial aspects of the CN that include the amount of net income and a prediction of the short-term expenses.	Economic
Innovation and Value Creation	The measure of the successful innovation and value creation actions within the CN. It represents the degree of new concepts, services or products and knowledge development that deliver value to the CN as a whole.	Economic
Conflict Risks	The level of risk of conflict situations within the CN environment. Avoidance or low-level risk of conflicts is one of the CN goals for sustainability. Might be activated whenever the other CN goals are put in jeopardy, like, for instance, in case of a low level of trustworthiness or problems in community building. The consequence is then reflected in the CN performance and value creation.	Economic Social
Level of Interactions	The level of connections and relations among CN members. Reflects the communication exchanges and collaboration dynamics across the CN.	Social

Table 7. *Cont.*

CN Goals	Definition	Sust. Pillars
Community Building	The level of community availability (or sense of community, or constructed linkages) within the CN environment. It also reflects the extent to which CN members can work together effectively by means of creating communities around a specific purpose.	Social
Knowledge Creation Potential	The potential level for generating new knowledge. Represents the degree of information, knowledge and resources made available for the CN either by CN members individually or by informal networks created within the CN acting as communities or groups of interest. The availability of resources and the exchange of knowledge/information contributes indirectly to the social cohesion and ecological sustainability. The potential of knowledge creation influences the economic pillar.	Economic Social Environmental

As in the case of the IMEA SD model, the initial values of these CN goals are initially equal to zero, then generated dynamically, taking into account the influence of the evidences input variables on these variables. This is further explained in the next sections.

4.2.2. Causal Loop Diagram

Like the IMEA SD model, the feedback structure of the ANEA SD model is qualitatively mapped using a causal loop diagram, as depicted in Figure 7. Positive linkages are represented with a "+" sign, while negative linkages are represented with a "−" sign.

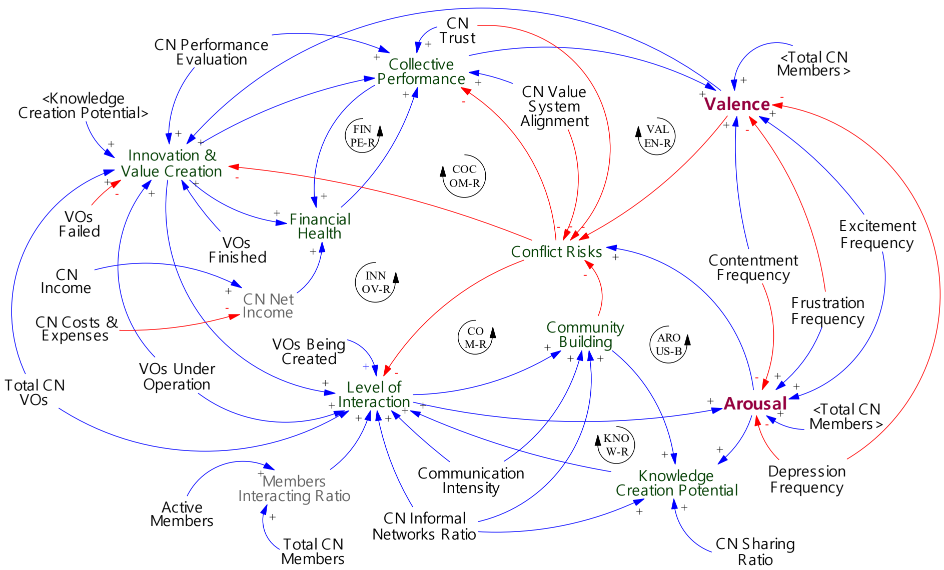

Figure 7. ANEA SD causal loop diagram

As it can be identified in the causal loop diagram of Figure 7, the main causal loops for the ANEA causal model are: collective commitment reinforcing loop (COCOM-R); financial performance reinforcing loop (FINPE-R); innovation reinforcing loop (INNOV-R); community reinforcing loop (COM-R); knowledge generation reinforcing loop (KNOW-R); valence reinforcement loop (VALEN-R); and arousal balancing loop (AROUS-B). A detailed description of each identified causal loop is presented below (Table 8):

Table 8. Description of each ANEA model causal loop.

Collective Commitment Reinforcing Loop (COCOM -R)	This reinforcement loop models the dynamics between collective performance, valence, conflict risks, and innovation and value creation, reflecting the notion of collective commitment. As innovation and value creation increase (decrease), a boost (blow) in collective performance potentially happens within the CN. With the improvement (worsening) of the collective performance, the valence dimension of the ANE tends to augment (diminish), due to being directly connected with the level of collective pleasantness. With a good (bad) valence, the risks of conflict situations within the CN environment diminish (augment). As the risks of conflict conditions decrease (increase), the CN environment gets healthier (sicker), leveraging (not leveraging) innovation and value creation.
Financial Performance Reinforcing Loop (FINPE -R)	This loop reinforces the dynamics between financial health and collective performance. Taking into account that financial health is a major objective of the CN that is being modeled, the better (worse) it is, the better (worse) the mechanisms for motivation and control of collective performance are. The higher (lower) the collective performance is, the healthier (sicker) the financial situation.
Innovation Reinforcing Loop (INNOV-R)	This reinforcing loop models the dynamics of the interaction level within the CN, community building, conflict risks, and innovation and values creation, reflecting the notion that without a healthier atmosphere among CN members, innovation and value creation suffer some consequences. As the level of interactions inside the CN increases (decreases), the potential for community building also increases (decreases), due to the strengthening (weakening) of bonds among members. Whenever the level of community building is high (low), the potential of conflict within the CN diminishes (augments). As the risk of a conflict situation decreases (increases), the atmosphere for innovation and value creation within the CN increases (decreases). With an increase (decrease) in innovation and value creation, there is the necessity for more (less) interaction among members, in order to pursuit the innovation requirements.
Community Reinforcing Loop (COM-R)	This reinforcement loop models the dynamics of community building, conflict risks, and level of interaction, reflecting the conditions that are important for community strengthening within the CN environment. Thus, as the level of interactions among CN members increases (decreases), the potential for the community to gain stronger ties also increases (decreases). As the community gets stronger (weaker), the risk of conflict diminishes (augments). As the conflictual risks decrease (increase), the interactions and relationships among members are strengthened (weakened) accordingly.
Knowledge Generation Reinforcing Loop (KNOW-R)	This reinforcement loop models the dynamics of the level of interactions, community building and knowledge creation potential, reflecting the conditions to reinforce the generation of knowledge. In this way, as the quality and intensity of interactions increases (decreases) the potential for strengthening (weakening) community ties increases (decreases). With the increase (decrease) of the sense of community and its ties, the likelihood of generating knowledge also increases (decreases). The augmentation (diminishing) of knowledge creation leads to more (less) interactions among members.
Valence Reinforcement Loop (VALEN-R)	This reinforcement loop models the dynamics of collective performance, valence, and risk of conflict situations, reflecting the conditions that influence (positively or negatively) the valence dimension, i.e., the pleased–unpleased level of the aggregated networked emotion. In this sense, as the collective performance gets higher (lower) the CN valence augments (diminishes). By lowering (raising) the risks of conflict, the collective performance actions tend to increase (decrease) accordingly.
Arousal Balancing Loop (AROUS-B)	This balancing loop models the dynamics among the interaction level, arousal and conflict risks, reflecting the tendency of the dynamic dimension of the aggregated network emotion. As the potential for conflict increases (decreases), the level of interaction among members is negatively (positively) affected. With the diminishing (increasing) interaction level, the arousal is influenced negatively (positively). When the level of arousal decreases (increases), it might influence the risks of conflicts either positively or negatively depending on the value of the valence. In other words, as arousal represents the aggregated level of excitement or enthusiasm of the CN, when matched with the valence it might leverage the risk of conflict. For instance, if the arousal is positive but valence is negative, the ANE of the collaborative environment is frustration, meaning that the probability of conflict is high.

4.2.3. Stocks and Flows Diagram

This modeling phase consists of setting up a complete formal model with equations, parameters and initial conditions that represent the ANEA SD system. As the ANEA SD causal loop diagram only captures the mental models through the relationships among the different identified variables but does not allow distinction between the different types of variables, it is necessary to develop a stocks and flows diagram. This diagram follows the same line of thought used for the IMEA SD models previously presented.

As such, the ANEA stocks and flows diagram is presented in Figure 8. This diagram is built based on the ANEA SD causal loop diagram of Figure 7. It consists of two output state variables—*Valence* and *Arousal*—and four other state variables: *InnovValueCreation*, *CollectivePerf*, *ConfRisks* and *InteractLevel*. In this way, there are six structures of stocks-and-flows in the ANEA SD stocks and flows diagram.

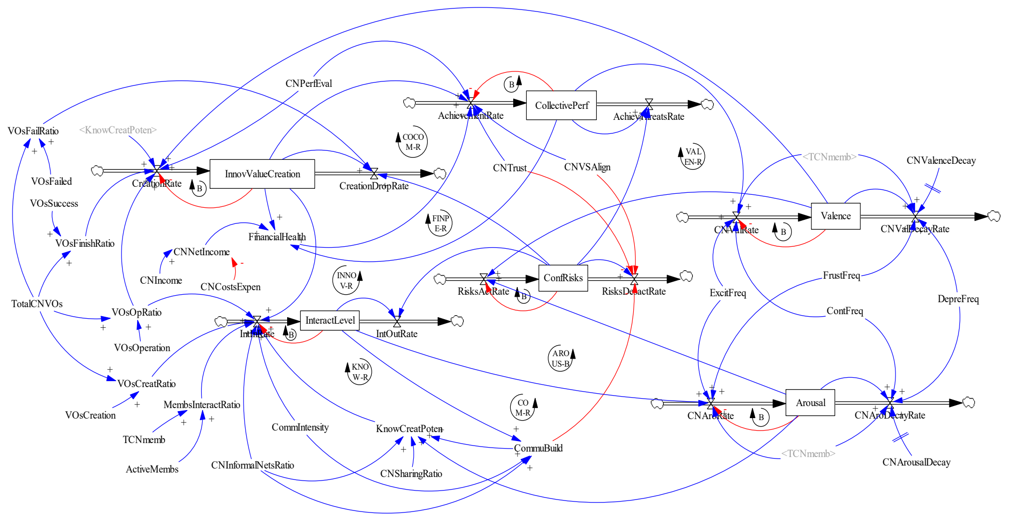

Figure 8. ANEA stocks and flows diagram.

These six structures are modeled with the quantification of its structures. This quantification is formalized with a set of equations that should not be considered as the only quantitative solutions, but rather as examples of how this could be performed. Furthermore, the values of each weight and the intervals of action of each variable will also depend on the requirements, data availability and objectives of each CN environment to be modeled and have to be calibrated accordingly.

An example of a structure quantification—the *InnovValueCreation*—is presented below.

Stock and Flow Structure of Innovation and Value Creation

The *InnovValueCreation* (innovation and value creation) stock is fed by the *CreationRate* inflow and is deflated by the *CreationDropRate* outflow, as illustrated in Figure 9.

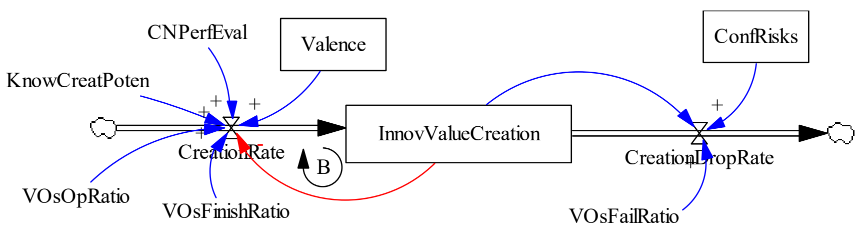

Figure 9. Stock and flow structure of innovation and value creation.

The *InnovValueCreation* stock variable is then the integral of the difference of *CreationRate* and *CreationDropRate* added to the initial value of the stock, represented below in Equation (5).

$$\begin{aligned} MembSatisf(t) &= MembSatisf(0) \\ &+ \int [SatisfRate(t) - DissatisRate(t)]dt \\ \text{where,} \quad MembSatisf \in \mathfrak{R} &\wedge \{0 \leq MembSatisf \leq 1\} \end{aligned} \tag{5}$$

The *CreationRate* inflow is governed by the contributing factors of innovation and value creation. The main contributing factors for innovation pass by, forming solid teams of organizations capable of bringing more diverse knowledge and experience, and also of breaking down knowledge silos. As a consequence, fresh new ideas arise that need to be put forward in order to create value for both the members of the CN and the customers. Therefore, the creation of value is given by the sum of the value added from existing products or services and the creation of new ones. Having this in the background, the *CreationRate* inflow is divided into two main perspectives: (*i*) the generation and implementation of new ideas collaboratively and, (*ii*) the creation of value. Equation (6) formalizes the *CreationRate* inflow.

$$\begin{aligned} & CreationRate(t) \\ & \qquad = (IdeaGenerator(t) + ValueCreat(t))/2 \\ & \qquad -InnovValueCreation(t) \\ \text{where,} \quad & CreationRate \in \mathfrak{R} \end{aligned} \tag{6}$$

The *IdeaGenerator* term captures the collaborative generation and implementation of new ideas. It is determined by the weighted average of the potential of knowledge creation (*KnowCreatPoten*) value, of the ratio of VOs under operation (*VOsOpRatio*) and of the level of the aggregated pleasure of the CN (*Valence*), adjusted to fit within the order of magnitude of the other variables. Furthermore, for this model it is considered that the weights of the *KnowCreatPoten* and the *VOsOpRatio* are superior to the *ValenceAdj*, as described in Equation (7).

$$\begin{aligned} & IdeaGenerator(t) \\ & = \frac{\left(w_i \times KnowCreatPoten + w_j \times VOsOpRatio + w_k \times ValenceAdj\ (t)\right)}{w_i + w_j + w_k} \\ \text{where,} \quad & IdeaGenerator, w_i, w_j, w_k \\ & \in \mathfrak{R} \wedge \{0 \leq IdeaGenerator \leq 1\} \\ & \wedge \left\{w_i, w_j > w_k\right\} \end{aligned} \tag{7}$$

The *ValueCreat* term captures the value created inside the CN. It is determined by the weighted arithmetic mean of the existing products and services, represented by the rate of VOs that have already terminated (*VOsFinishRatio*), the ongoing creation of new products and services, represented by the VOs under operation (*VOsOpRatio*), the overall performance evaluation of the CN (*CNPerfEval*) and of the level of aggregated pleasure of the adjusted CN (*ValenceAdj*). Furthermore, for this model it is considered that the weights of the *VOsFinishRatio* and the *VOsOpRatio* are superior to the others, as described in Equation (8).

$$\begin{aligned} & ValueCreat(t) = \left(w_i \times VOsFinishRatio + w_j \times VOsOpRatio \right. \\ & \left. +w_k \times CNPerfEval + w_y \times ValenceAdj\ (t)\right)/w_i \\ & +w_j + w_k + w_y \\ \text{where,} \quad & ValueCreat, w_i, w_j, w_k, w_y \\ & \in \mathfrak{R} \wedge \{0 \leq ValueCreat \leq 1\} \\ & \wedge \left\{w_i, w_j > w_k, w_y\right\} \end{aligned} \tag{8}$$

The *CreationDropRate* outflow is driven by the costs of VOs failing (*VOsFailRatio*) and by the conflict risks (*ConfRisks*) negatively influencing the creation of value and innovation. The higher (lower) the *ConfRisks* and the *VOsFailRatio* are, the more (less) the *InnovValueCreation* diminishes. In this case, it was considered that the weight of *ConfRisks* would be superior to the *VOsFailRatio*, as represented in Equation (9):

$$\begin{aligned} & CreationDropRate(t) \\ & \qquad = \left(w_i \times ConfRisks(t) + w_j \times VOsFailRatio\right) \\ & \qquad /w_i + w_j \times\ InnovValueCreation(t) \\ \text{where,} \quad & CreationDropRate, w_i, w_j \in \mathfrak{R} \wedge \left\{w_i > w_j\right\} \end{aligned} \tag{9}$$

As in the IMEA SD model, this quantification, i.e., the equations that are being proposed, should not be considered the only quantitative solutions. Rather, they are examples of how this modeling approach could be performed. In addition, the values of each weight and the intervals of action of each variable will also depend on the requirements, data availability and objectives of the CN to be modeled. For the specific case of this ANEA SD model, the values of the weights are not the focus, instead, the focus relies on guaranteeingthat this modeling framework and simulation approach is valid and promising.

4.3. CN (Collaborative Networks) Representation with Agent-Based Modeling

The agent-based modeling (ABM) approach is used as a potential solution for representing the abstraction of the considered CN and its involved participants, as proposed in the C-EMO framework, with a focus on the individual member's emotional influence on the overall emotional health of the CN and vice-versa.

In this context, using the ABM methodology is adequate because it allows (based on [54]):

- *Individual modelling*—each participant of the CN can be represented by an agent that has the characteristics (attributes and behaviors) needed to appraise the IME state (in the case of members) and the ANE state (in the case of the CN), the potential behavior, and the interactions with the other agents;
- *Flexibility*—meaning that it is possible to add or remove entities from the CN, or even change some features and characteristics of the network in order to help in simulation of a variety of scenarios;
- *Data distribution*—CNs are by nature distributed entities, containing distributed members with distributed data.

Considering this, individual entities are the CN members and the entity that represents the emotion management system within the CN (which, for simplification, is normally denominated as CN), and the population is the collection of individual entities that belong to the collaborative network. Thus, each CN individual member is represented by an agent, the CN by another agent, and the CN and the collection of members are represented by a population of agents that "live" inside the agent that represents the collaborative environment, as illustrated in Figure 10, below.

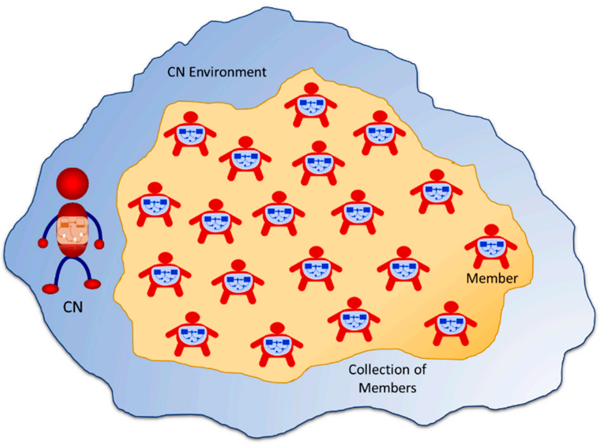

Figure 10. Agent-based illustrative view of the CN environment.

The model is then composed of three different types of agents:

- The *Individual Member Agent (IMAgent)*, which represents each participating individual member of the CN. This agent embeds the IME model with the IMEA SD model previously presented. It is modeled using two sub-agents: (i) *IPerceptionAgent*, which is the agent that is in charge of interacting with the CN environment and of collecting the data from the internal knowledge database and that creates the IME evidences vector, and (ii) *IEmotionAgent*, which is the agent that is responsible for the IME appraisal and where the IMEA SD model is implemented;

- The *CN Agent (CNAgent)*, which represents the CN's emotion management system. It also embeds the ANE model with the ANEA SD model presented before. It is modeled also using two sub-agents: (i) *CPerceptionAgent*, which is the agent that is in charge of interacting with the CN environment and of collecting the data from the internal knowledge database and that creates the ANE evidences vector, and (ii) *AEmotionAgent*, which is the agent responsible for the ANE estimation and where the ANEA SD model is implemented;
- The *CN Environment (CNEnvironment)*, which represents the CN itself, the CN agent and the collection of IMA agents that belong to the CN.

A UML (Unified Modeling Language) diagram of the overall ABM model structure is depicted in Figure 11. Each agent class is represented by a set of attributes and methods (behaviors, behaviors that modify behaviors, and update rules for dynamic attributes) that operate on the agent class.

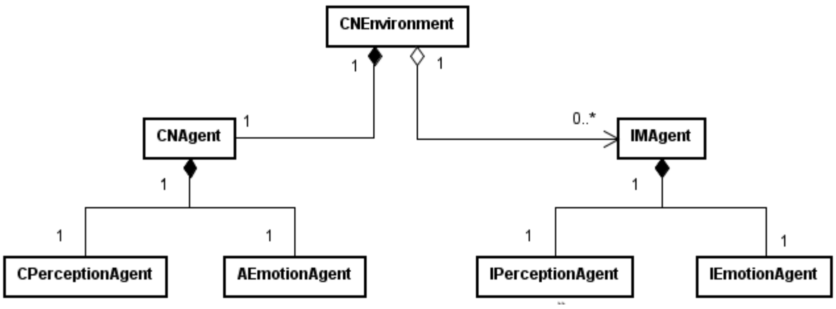

Figure 11. UML class diagram of the C-EMO agent-based model.

An overall picture of the above-mentioned agents is presented in the following sub-sections, with a focus on the *AEmotionAgent* and *IEmotionAgent*, which are the agents that implement the SD models presented previously.

4.3.1. Individual Member Agent

The IMA agent dynamics is based on the IME model of C-EMO, and its structure is presented in Figure 12. *Perception*, which handles the agent's interactions with the CN environment and with the other agents, is implemented by the IPerceptionAgent; *Emotion Appraisal*, which characterizes the reasoning module and is implemented by the IEmotionAgent; *Emotion Response*, which manages the response actions of the agent and, finally; *Knowledge & Database* deals with the management of the CN environment and the internal knowledge and data model.

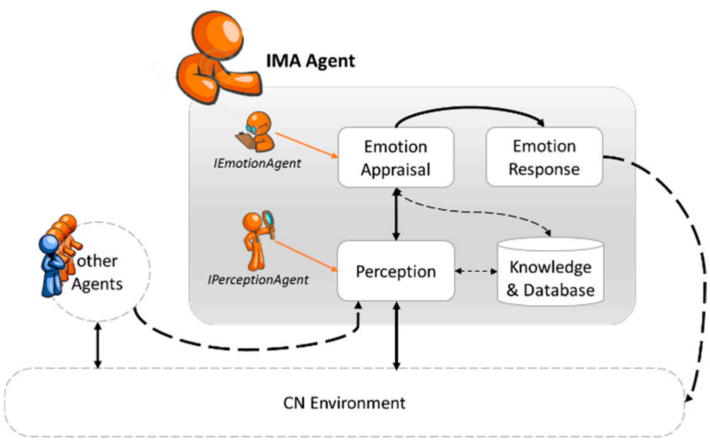

Figure 12. IMA (Individual Member Agent) agent structure.

Each agent class is represented by a set of attributes and behaviors. Figure 13 is an excerpt of the class diagram of Figure 11, describing in detail the attributes and the behavioral methods of the individual member agents.

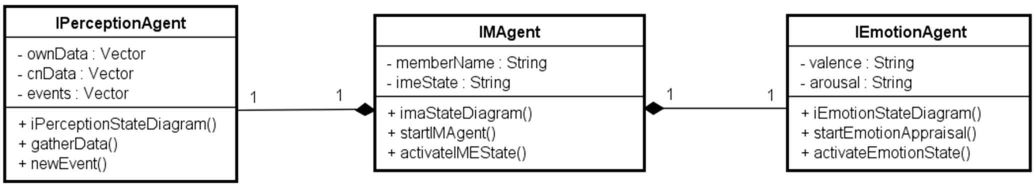

Figure 13. UML class diagram of the IMA agent and sub-agents.

For the purpose of this article, the IEmotionAgent is the one that is being described in detail. It is characterized by the following attributes: valence and arousal. Its behavior is conceptualized in the state diagram of Figure 14.

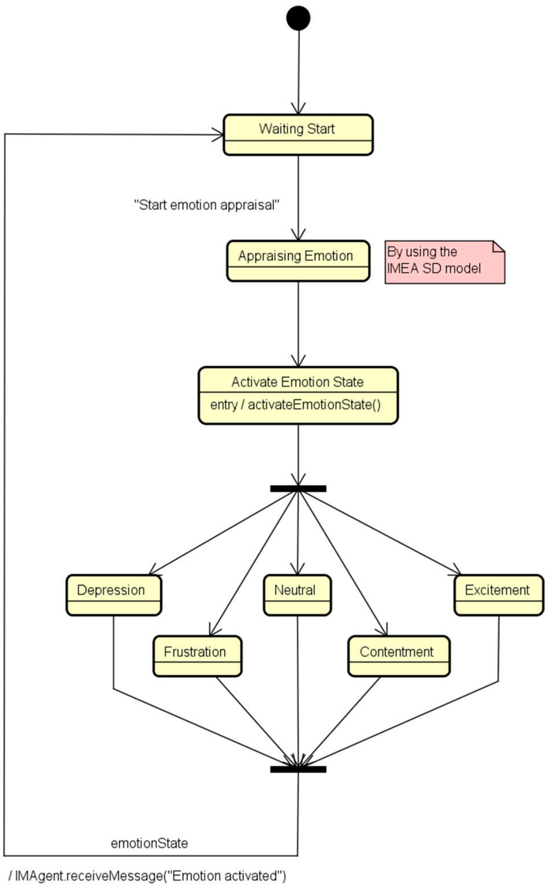

Figure 14. State diagram of the IEmotionAgent.

The IEmotionAgent state diagram, which represents the *iEmotionStateDiagram*() method, can be described as follows:

1. The IEmotionAgent remains in the "waiting" state until receiving the triggering message "Start emotion appraisal";
2. Then, the IEmotionAgent starts the emotion appraisal by using the IMEA SD model. As described in the IMEA SD model, the resulting variables are the tuple (valence, arousal), which are updated accordingly;

3. These variables are then used in the *activateEmotionState*() in order to select and activate the corresponding emotion state. This is done using the action chart described in Figure 15;
4. Finally, the IEmotion agent sends the message "Emotion activated" to the IMAgent, acknowledging that the current emotion has been estimated and activated and returns to the initial state.

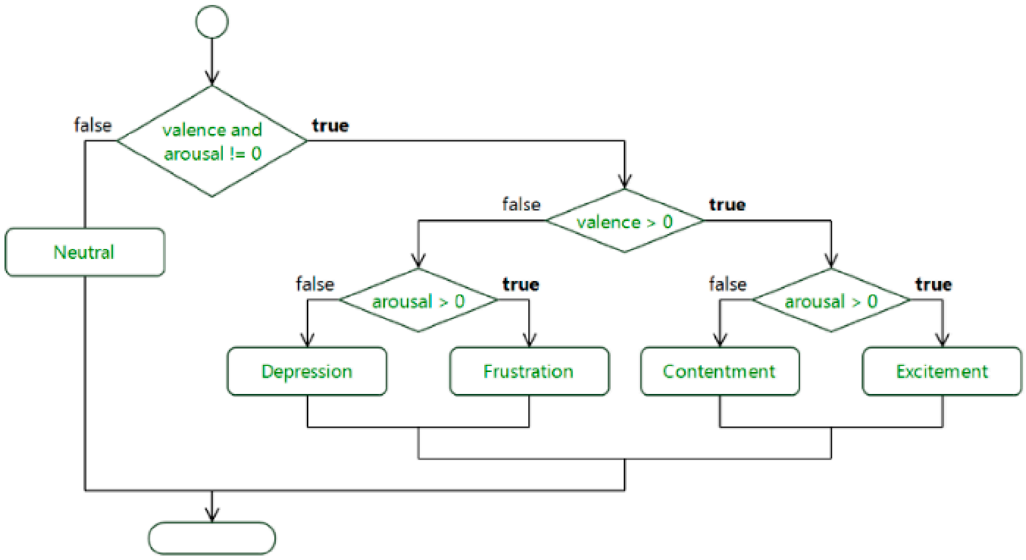

Figure 15. *activateEmotionState()* action chart.

4.3.2. Collaborative Network Agent

The CNA agent dynamics are based on the ANE model of C-EMO and its structure is presented in Figure 16; *Perception* represents the interactions with the CN environment and with the other agents and is implemented by the CPerceptionAgent, *Emotion Reasoning* characterizes the agent's specific task of running the appraisal models and is implemented by the AEmotionAgent, *Emotion Response* manages response actions and, finally, *Knowledge & Database* which deals with the management of the CN environment and the internal knowledge data model.

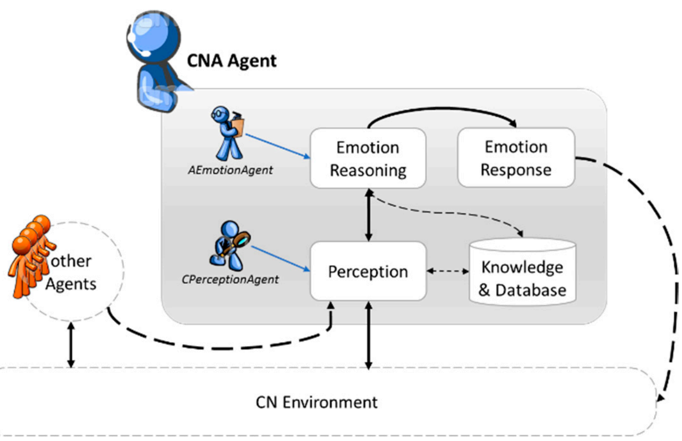

Figure 16. CNA agent.

Figure 17, is an excerpt of the class diagram of Figure 11, and describes the CNA agent classes in detail, showing their attributes and behavioral methods.

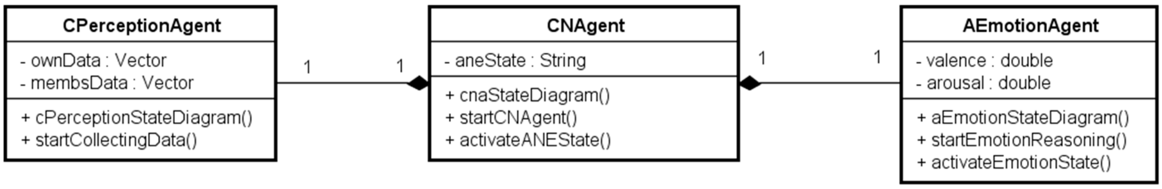

Figure 17. UML class diagram of the CNA agents and sub-agents.

Like the IMA agent, the AEMotionAgent is the agent that is described in detail for this article. It is characterized by the following attributes: valence and arousal. Its behavior is described in the state diagram of Figure 18.

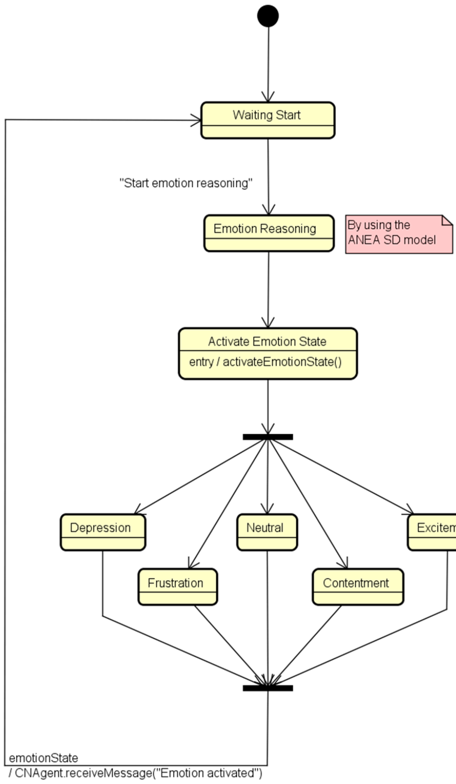

Figure 18. State diagram of the AEmotionAgent.

The AEmotionAgent's state diagram, which represents the *aEmotionStateDiagram()* method, can be described as follows:

1. The AEmotionAgent's initial state is waiting for the trigger message to start;
2. Then, the agent enters the emotion reasoning state and starts executing the ANEA SD model. The model result is the update of the agent's state variables—valence and arousal;
3. These variables are then used in the *activateEmotionState()*, which is described in Figure 15, in order to select and activate the corresponding aggregated emotion state;
4. Finally, the AEmotionAgent sends the message "Emotion activated" to the CNAgent, acknowledging that the current aggregated emotion has been estimated and activated, and returns to the initial state.

5. Implementation of the Simulation Model for CN Emotion Appraisal

The simulation model is implemented using the AnyLogic modeling software [33]. This simulator intends to execute the presented agent-based model and to mimic a CN environment comprising several individual members, geographically distributed. In addition, AnyLogic allows a graphical interface-based construction of hybrid simulation models which can be enriched by Java code blocks. It supports the development of component-based simulation frameworks, such as the components of the C-EMO framework, e.g., the ANEA SD and IMEA SD models, and the involved agent's behaviors. It approaches software and model development from an object-oriented perspective and includes facilities for implementing models based on UML conventions, such as state charts, inheritance, and transition diagrams [55].

Another interesting feature, which fits the purpose of this work, is that these AnyLogic models can be reusable and/or customizable in accordance with the specificities of each CN. This means that both the IMEA SD and ANEA SD models might be easily adjustable and customized, taking into consideration the nature of the specific CN to be simulated. In summary, the implementation of the simulation model is based on a set of technologies, which comprise AnyLogic 7.0 as the graphical interface-based multimethod simulation tool; Java as the programming language; and MySQL Workbench 6.0 as the workbench for object-relational databased management system (ORDBMS).

Figure 19 illustrates the graphical interface of the implementation of the *IEmotionAgent* and the corresponding IMEA SD model, and Figure 20 illustrates the AEmotionAgent and the corresponding ANEA SD model.

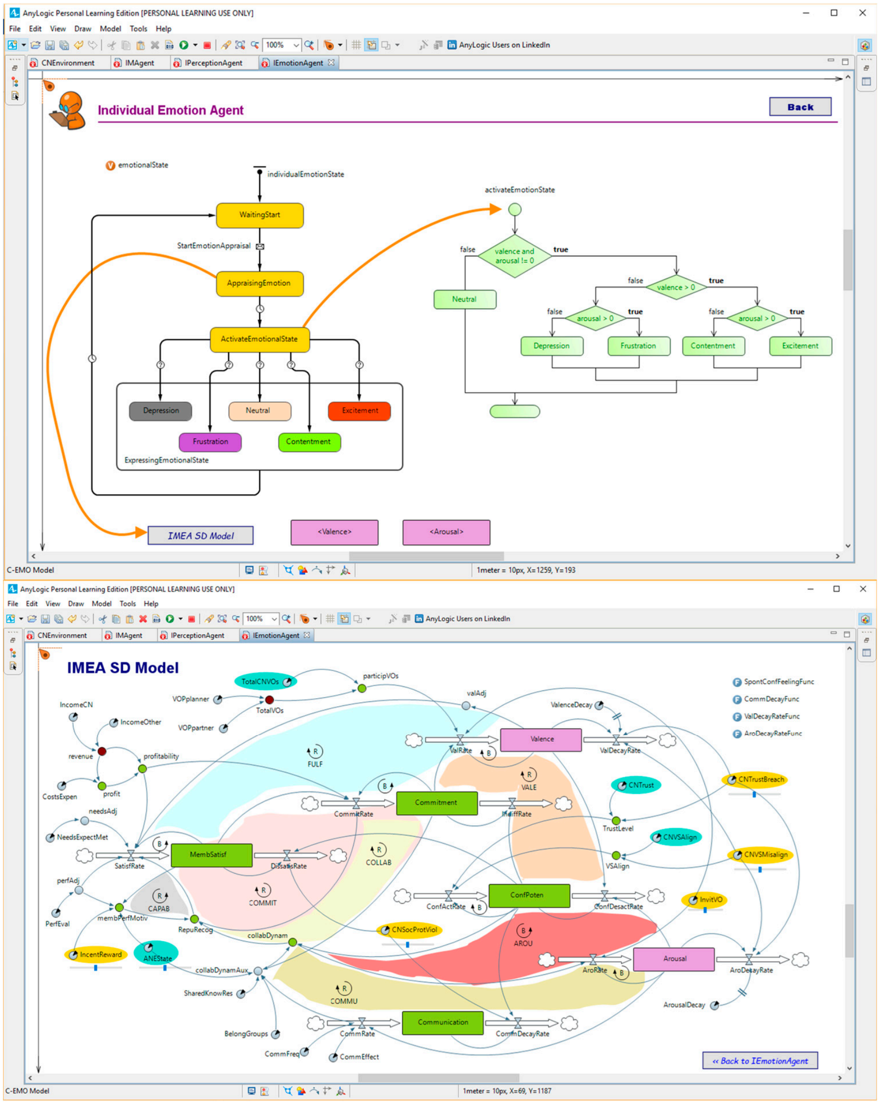

Figure 19. Graphical user interface of the implementation of the *IEmotionAgent* and the IMEA SD model.

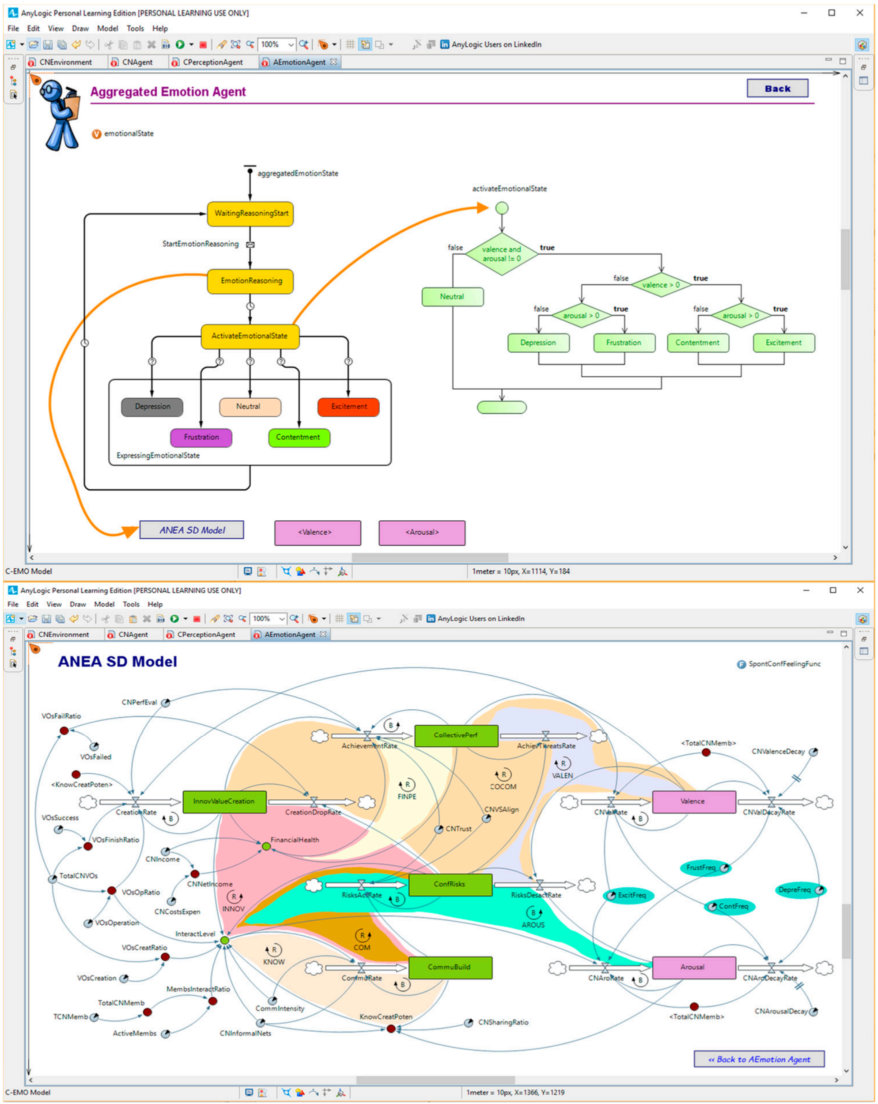

Figure 20. Graphical user interface of the implementation of the *AEmotionAgent* and the ANEA SD model.

6. Results and Discussion

One main difficulty in the process of testing the proposed simulation modeling approach is the lack of real data for performing benchmarking and tuning the model according to a real case. Therefore, the validation process depends on computational simulations of different scenarios, and a "kind of benchmarking" is done against pre-defined assumptions and expectations based on the theoretical foundation of the model. With this in mind, several simulation experiments are undertaken to analyze the simulation model in different setups. For this, a plan was initially formulated to gather the desired information and to enable the drawing of valid conclusions. This was done through the design of experimental models or scenarios. Then, the scenarios are executed in the proposed simulation model, and a sensitivity analysis and discussion of their results is performed.

6.1. Scenario Design

Two sets of experiments are considered: one concerning the CN individual members, to verify and validate the IMEA SD model (which is the model that materializes the IMEA element of the framework), and another related to the CN environment, aiming to verify and validate the ANEA

SD model (which materializes the ANEA element of the framework). In addition, with this set of experiments, it will be possible to identify the quality of the proposed agent-based model.

6.1.1. Individual Member Experiment

This experiment considered a CN member named Company *A*, with the following profile: "Company A is from India and has recently joined the CN. For the moment this company is getting in touch with the CN activities and trying to enhance its competences in order to be aligned with the CN value system and also to be prepared to get invited to form a VO. In the meanwhile, it has been sharing some resources in an informal network that it initiated. The level of trustworthiness among members of the CN is a very important issue". Having the member profile established, the initial conditions for the member's representative IMA agent are then created by populating the variables of the evidences vector according to the respective member's profile, as illustrated in Table 9.

Table 9. Initial conditions for Agent A (representing Company A).

Type		Name	Initial Condition
Input		Agent Initial State	1 IMAgent is instantiated and, consequently, the two sub-agents iPerceptionAgent and iEmotionAgent. The initial IMEState is Neutral and the memberName is Company A.
Output		IME State	The activated emotion that is delivered from the iEmotionAgent sub-agent, corresponding to the values of the tuple <Valence, Arousal>.
Parameters	**Own Data**	ValenceDecay	0.2
		ArousalDecay	0.2
		VOPplanner	1 (VO under creation that is being planned by this company)
		VOPpartner	3 (Partner of VOs that have successfully finished)
		PerfEval	0.8
		NeedsExpectMet	0.8
		Profitability	0.8
		BelongInformalNets	0.75 (Belongs to three informal nets out of a total of four)
		SharedKnowResour	0.16 (Shared one resources and knowledge out of a total of six)
		CommFreq	0.8 (is being extremely participative and active)
		CommEffect	0.2
	CN Data	TCNMemb	5
		TotalCNVOs	6
		ANEState	Neutral
		CNTrust	0.8
		CNVSAlign	0.8
	Events	InvitVO	0 (event not active)
		IncentReward	0 (event not active)
		CNSocProtViol	0 (event not active)
		CNTrustBreach	0 (event not active)
		CNVSMisalign	0 (event not active)

With the initial conditions established, three distinct scenarios are proposed for Company A represented by the *IMAgent A*, as described in Table 10. For each scenario, a sensitivity analysis of the involved variables is defined, and the expected IME state outcome for the corresponding scenario is envisaged.

Table 10. Scenarios for the Company A member represented by the IMAgent A.

Scenario	Description	Sensitivity Analysis	Expected Outcomes
S.1.1	This scenario runs the initial condition of the involved agent	Initial conditions from the involved agent	Frustration
S.1.2	During the runtime the involved agent receives an invitation to participate in a VO	InvitVO varies from 0 to 1 (deactivated to activated)	Excitement
S.1.3	Serious conflicts occurred between partners of a VO and the CN due to lack of transparency in some royalty issues . . . This activated a trust breach in the CN environment.	CNTrustBreach varies from 0 to 1 (deactivated to activated)	Depression

6.1.2. Collaborative Network Experiment

This experiment comprises a collaborative network named *SimulCN* with the following profile: "This collaborative network is formed by 5 members including Company A. The SimulCN has a total of 6 VOs, 5 of them have successfully terminated and 1 is being created. The participation of these members in the CN activities is quite shy with a reduced number of knowledge sharing and resources. The initial member's emotional states are one member with frustration (IMAgent A), one with depression and the other three members have the contentment state." Similarly to the individual member's experiment, there is a need to define the initial conditions of the CNA agent that embodies the SimulCN, as described in Table 11.

Table 11. Initial conditions for the agent representing the SimulCN.

Type		Name	Initial Condition
Input		Agent Initial State	1 CNAgent is instantiated and, consequently, the two sub-agents cPerceptionAgent and aEmotionAgent. The initial ANEState is neutral.
Output		ANE State	The activated aggregated emotion that is delivered from the aEmotionAgent sub-agent, corresponding to the values of the tuple <Valence, Arousal>.
Parameters	**Own Data**	ValenceDecay	0.2
		ArousalDecay	0.2
		TCNmemb	5 (The total number of members)
		ActiveMembs	4 (The IMAgent A, IMAgent B and other two)
		TotalCNVOs	6
		VOsSuccess	5
		VOsOperation	0
		VOsFailed	0
		VOsCreation	1
		CNPerfEval	0.6
		CNTrust	0.8
		CNVSAlign	0.8
		CNSharingRatio	0.2 (The total of shared assets is six)
		CNInformnalNets	0.7 (The total of Informal nets is four)
		CommIntensity	0.5 (Overall communication)
		CNProfitability	0.6
	Member	ExcitFreq	0
		ContFreq	3
		NeutralFreq	0
		FrustFreq	1
		DepreFreq	1

Three scenarios are proposed for the SimulCN, represented by the *CNAgent SimulCN*, as described in Table 12. In the same vein as the previous experiments, a sensitivity analysis of the involved variables is defined and the expected ANE state outcome for the corresponding scenario is predicted.

Table 12. Scenarios for the SimulCN collaborative network represented by the CNAgent SimulCN.

Scenario	Description	Sensitivity Analysis	Expected Outcomes
S.2.1	This scenario runs the initial condition of the involved agent.	Initial conditions from the involved agent.	Contentment
S.2.2	During the runtime the VO under creation failed, thus the level of values alignment and trust decreases substantially.	CNTrust, CNVSAlign decreases a portion of its current value. VOsCreation diminishes 1 and VOsFailed augments 1.	Depression/ Contentment?
S.2.3	During the runtime there is a shift in members' IME states from contentment to depressed.	ContFreq decreases in the same value that the DepreFreq increases.	Depression

6.2. Simulation Runs and Sensitivity Analysis

Simulation runs consist of executing the simulation model to generate the inferred data and to perform a sensitivity analysis. The sensitivity analysis consists of making changes to the model's inputs (using the scenarios designed in the previous section), running those scenarios, inspecting the results by checking the results are compliant with the expectations, and learning from and discussing the results. The time unit selected to run these scenarios in days.

6.2.1. Individual Member Scenario Run

This experiment starts with the configuration of the initial values of the IMAgent A's parameters. Figure 21 illustrates the scenarios S1.1, S1.2 and S1.3 for the IMAgent A.

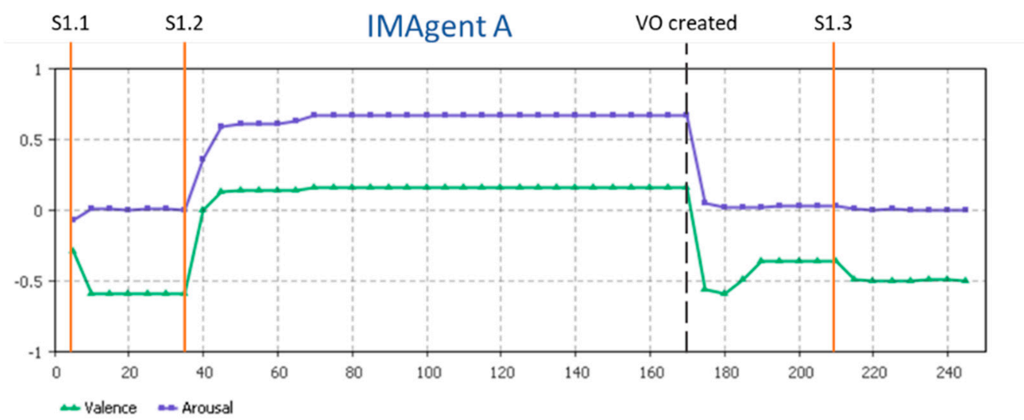

Figure 21. IMAgent A scenarios simulation results.

At the beginning of the simulation run, which corresponds to the S1.1, the value of the tuple (valence, arousal) corresponds to *frustration*, as expected. This agent represents a company that has joined the CN a few days ago, so its metrics are still below average. Nonetheless, following Scenario S1.2, it receives an invitation to form a VO and, as can be seen in t = ~35, both valence and arousal increase substantially (activating the *excitement* IME), denoting both the satisfaction and the stimulus that this event provoked in company A. Then, for a considerable period of days, its IME state remains stable. After a couple of months, the VO is finally created, and is reflected in the results with the decrease in valence and arousal at t = 170, activating the *frustration* IME. Meanwhile, some metrics are updated, such as the number of VOs or the CN income, shown in the increase in valence in t = 180. However, company A is still frustrated; it is still a young company in the CN and its goals are not yet met. Finally, the occurrence of a CN trust breach (S1.5) at t = 210, conducts the IMAgent A state to *depression*, as expected.

6.2.2. Collaborative Network Scenario Run

This experiment starts with the configuration of the initial values of the parameters of the collaborative network *SimulCN*. Figure 22, illustrates the scenarios S2.1, S2.2 and S2.3 that were simulated for the SimulCN agent.

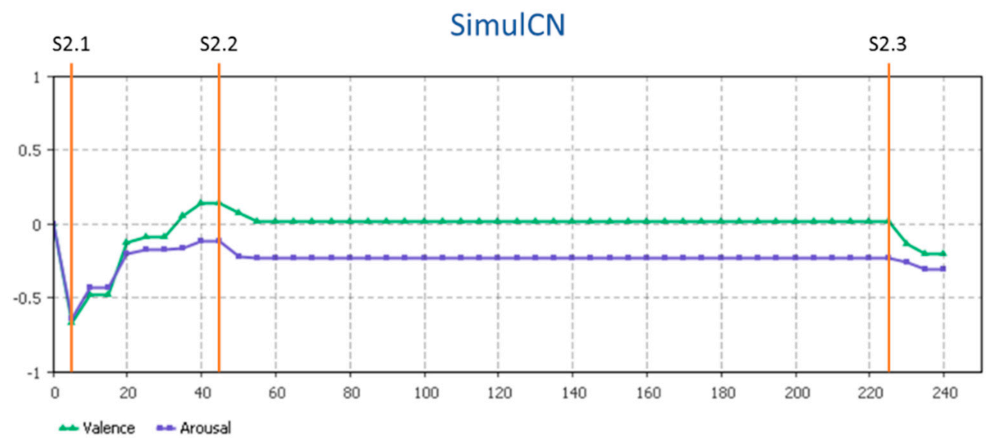

Figure 22. SimulCN CNAgent scenarios simulation results.

Initially, with the simulation run of the initial conditions (S2.1), it can be seen that both valence and arousal took a period of time before reaching the *contentment* ANE state (as expected) around t = 35. This unstable period has to do with the initial dynamics of the involved members. When Scenario S2.2 is put in practice, i.e., when the only VO under creation fails and the levels of trust and values alignment of the VO decrease substantially, both valence and arousal decrease and the ANE remains in the *contentment* state, although with a reduced value of valence (it can suddenly change to depression, which is what was expected). After a period of days, changes in member's IME affects the dynamics of the ANE, as simulated with the S2.3. What happens is a shift from contentment to depression states in two members, which is translated into a negative reaction of both valence and arousal, conducting the ANE state in SimulCN to *depression*.

As a final remark on this analysis and comparing with what was expected from the experiments design, it can be said that the resulting behavior of both the IMEA and ANEA SD models are adequate and positively valid. Nevertheless, there are some improvements that are needed for future development in order to transform them into more accurate models. Some examples are: (*i*) refinements of the IMEA and ANEA SD models, in order to have smoother transitions whenever the events occur; (*ii*) the creation of a new dimension of CNE (collaborative network emotion) that represents intensity of emotion (e.g., strong, moderate and weak). This dimension, in conjunction with the other two (arousal and valence), could give more information about the emotion that is being felt.

7. Conclusions and Future Work

Aiming at implementing the C-EMO modeling framework, two modeling and simulation approaches were considered: the agent-based and system dynamics. The first one uses agents to represent the CN players and their behavior, and the second one models the emotion reasoning element of each agent. In other words, the agent-based approach models the C-EMO framework constructs have, embedded in each agent, the system dynamics model for emotion reasoning. Two system dynamics models are proposed: the ANEA SD model for appraising the aggregated network emotion of the CN environment and, the IMEA SD model for assessing the individual member's emotion. Both models were designed to estimate the pair (valence, arousal) of collaborative networked emotions (CNEs) by modeling the causal influences of the gathered evidences, i.e., the information that is provided by the management system of the collaborative network. These models also reflect the influence of disrupting events in the CN environment, such as the violation of a social protocol, as well as the influence that the aggregated network emotion has on each particular member and, on the other hand, the effect that each member's emotion has on the overall aggregated emotion.

The validation of the achieved solutions was conducted, taking into consideration that, to the best of the authors' knowledge, this is a pioneering research work, meaning that no other works concerning the study of emotions applied to organizations (and not to humans) in the context of CNs with a non-intrusive characteristic have been found by the authors so far. In addition, there is no substantial available historic information regarding CNs and their respective members that could be used to validate the proposed emotion modelling approaches in a real context. Furthermore, this work is not intended to show the most accurate or the most adequate model of emotions in CNs—that would be too ambitious, considering the amount of knowledge from different scientific areas that would be needed. Instead, it intends to provide a first step in the research area, providing a modeling framework on top of which new models and technologies can be built.

This work was also partially validated in EU and national research projects, in terms of direct interaction with potential users of this modeling framework, and by industry stakeholders, in a workshop that took place in Chennai, India, within the activities of the GloNet project, where a brief presentation was conducted for 34 participants of a network of solar companies. After the presentation, participants answered a questionnaire comprising some essential questions about the fitness-for-purpose of this work and the overall results were quite satisfying. For instance, some results are: 50% of participants agree that this is a promising research area, 10% totally agree and 20% are neutral; 66.67% agree that the modeling framework designed to assess emotions is adequate and 25% are neutral; 58.34% agree that the information from CN members should be collected in a non-intrusive way and 33.33% are neutral. One participant expressed doubts about the applicability of this framework in the Indian context, due to different cultural aspects and different business practices. This is an issue that needs to be better explored in future research.

Regarding future research, some aspects are identified as needing to be improved and others to be explored. Some aspects needing to be explored are: (*i*) the introduction of a third dimension, *intensity*, to the dimensional model of CNE (as seen in the validation); (*ii*) integration of social network analysis tools such as Pajek or SocNetV, in order to give more accurate inputs to the reasoning modules; (*iii*) creation of an emotional competences framework, to help in the characterization of the "emotional maturity" of each CN member; and (iv) self-regulation processes of emotions. Concerning improvements, they are strongly connected to refinements needing to be performed on the SD models in order to have smoother transitions.

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