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Application of adaptive temporal-causal network model for extreme emotion handling

Master’s Thesis in Computational Science

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Abstract: Stress has been seen as a negative factor which affects every person's life quality and decision making. To help avoiding of extreme emotions caused by external stressor, a number of practices have been introduced - in the scope of this study we take into account three therapy kinds: mindfulness, humour and music therapy. We aim to study how in fact various practices help people to cope with stress, using mathematical modelling. We come up with a practical implementation in a form of a client-server software, incorporating the computational model which describes therapy effects for overcoming stress based on quantitative neuropsychological research. The application objective is to help users overcome stressful events in their life while collecting empirical data to support further research and model development. The underlying network model simulates the elicitation of an extreme stressful emotion due to a strong stress-inducing event as an external stimuli, following then with a therapy practice simulation leading to a reduction of the stress level. Each simulation is based on user input and preferences, integrating a parameter tuning process, it fits a simulation for a particular user.

Keywords: Integrative model, computational model, temporal-causal network, network-oriented modelling, cognitive modelling, stress, mindfulness, humour, music, emotions

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1 Introduction

In the 21st century stress has become one of the major threats to the mental well-being of our society, affecting both students (see Rückert 2015) and working adults, causing major health issues (see Kivimäki and Kawachi 2015). Oxford dictionary defines stress as a state of mental or emotional strain or tension resulting from adverse or demanding circumstances. As emphasized by McEwen et al. (2015), the primary result of stress is structural changes in the neural architecture of our cognitive systems, which if persist after the stress ends may indicate failed resilience of the neural system. As stated by Hanser (1985), excess stress on its later stages without appropriate reaction contributes to the development of physical conditions such as hypertension, ulcers, skin disorders, headaches, arteriosclerosis, and other severe diseases. Generally stress may be divided into "good stress", "tolerable stress" and "toxic stress" (see McEwen 2002). It is indicated by McEwen that stress from the early years of life can alter neural architecture and increase adverse reactions to external stressors, escalating in this way to a toxic stress. It is even more important to learn how to deal with stress starting in younger age as students are more vulnerable to stress-inducing external stimuli because of the stressful environment (see Ross, Niebling, and Heckert 1999; Sivoňová et al. 2004). Thus, stress becomes a subject with increased concern in the modern society and draws attention of researches with different backgrounds.

In this study we address this subject with a Network-Oriented Modelling approach by describing the underlying causal connections in cognitive system of a stressed person, with computational model. We use a temporal-causal network model based on the Network-Oriented Modelling approach as described in the book (*Network-Oriented Modeling* 2016). Causal modeling and causal reasoning have a long tradition in science as may be seen from works of Kuipers and Kassirer (1984), Bentler (1980) and Read (1987). The above mentioned approach could be considered a continuation of this tradition, incorporating knowledge from different domains and adopting foundations from Computer Science and Mathematics as well as Neuroscience, Psychology and Social Sciences. Furthermore, in order to describe cognitive behaviour patterns, it adds the dynamic and adaptive temporal perspective on mental states by means of cyclic causal connections, as described by Kim (1996).

We designed and developed a client-server application which provides an interface for interaction with the model. Architecture of the resulting multi-agent system consists of three main parts:

- Analysis part, includes user information gathering and studying, along with simulation assessment.
- Support part, contains communication with the user, including therapy advice.
- Adaptation part, consists of the adaptation algorithms applied to tailor simulation for a particular case.

Thus, we integrate the dynamic model of the domain into an intelligent application to make the application human-aware. By incorporating the domain model into the application, the intelligent system gets insight information about ongoing processes in surrounding environment of the agent. In our case we incorporate the domain model into the ambient application as three sub-models or components for analysis, support and adaptation. The domain model specifically models human behavior directly as an agent model to simulate human behavior. This is derived from the Chapter 16 "Making Smart Applications Smarter" of the book *Network-Oriented Modeling* (2016). Below on Figure 1, the architecture of the multi-agent system is depicted as described previously.

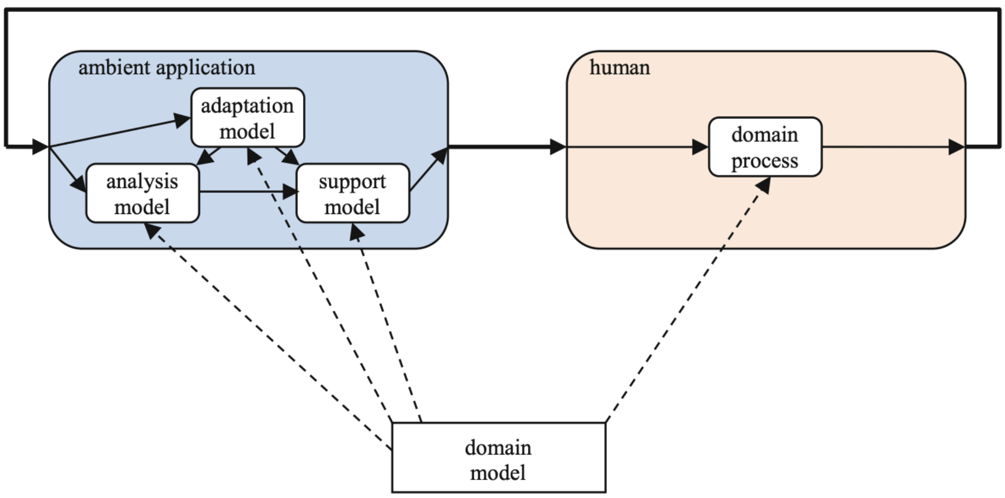

Figure 1. Integrative model system architecture (*Network-Oriented Modeling* 2016)

An analysis model performs analysis of the human's cognitive states and processes by reasoning based on observations and the domain model. Returning to the example of the emotion model, an analysis model for this domain is able to reason about a person's state of emotion based on empirical data collected over time. Then a support model generates therapy advice for the person by reasoning based on the domain model. A support model can use information from the analysis and human agent models to reason about support possibilities. (see Bosse et al. 2012).

Then, the software architecture of the application could be divided as follows:

- Front-end graphical user interface (GUI), serves as a communication point between user and the model.
- Server-side and application programming interface (API), contains all the logic and data manipulations, connects to the model.
- Computational model, which consists of the parameter tuning part and the model itself.

The ultimate goal of the developed software system is to help users deal with stressful events occurring in their daily life. To serve this goal it constantly gathers information from the user regarding their current emotional state and their preferences for different therapy kinds. After the data analysis has been carried, therapy advice is communicated to the user based on their current situation. It is worth noting that all the emotional state assessment is strictly subjective as it is done by the user themselves. Furthermore all the empirical data collected will be studied and used for the purpose of research to advance the simulation methods and expand scientific knowledge base on the subject of extreme emotions. Thus, both scientific and practical relevance of the research. Uniqueness of the research lies in the implemented comprehensive interface for the computational model (or the so-called multi-agent integrative model) as well as in the computational model and its parameters tuning.

This paper has the following structure: first after the introduction, in Chapter 2 we describe studied background literature and supportive research on the topic of extreme emotions handling. Then, in Chapter 3 the software architecture and decisions are expressed. After that comes Chapter 4 with detailed description of the computational model followed by Chapter 5, which contains specific information about the parameters tuning part of the model. Lastly, we conclude with discussion in Chapter 6.

2 Literature Study

The structure of the implemented network model including the cognitive states and connections showing the interactions between the states is justified based on the quantitative research available at the moment in the fields of Psychology, Neuroscience, Social Sciences, Computational Science. In this chapter we describe these works and show the supporting evidence for the network model design. High number of temporal-causal network-oriented modeling literature on therapies to decrease stress have been published recently, including the papers which contain detailed description in principle of the therapies which we take into account in this work, namely: mindfulness, humour and music therapy (see Mohammadi Ziabari and Treur 2018a, 2019; Andrianov, Guerriero, and Ziabari 2020). The ultimate idea behind these types of research is to study the undergoing cognitive processes during various therapy practices on extreme emotions handling. The mechanism of these therapies is as follows: a person, considered to be under stress due to external stimuli, starts occasionally performing one of the therapies. After a therapy session the stress level decreases, thus helping the person to suppress extreme emotions. Another assumption which proved to be rightful is that after repeating these therapy sessions for a while, the person's stressful feelings are not as intense as before they started practicing the therapy. Moreover, the individual does not get stressed as easily too, thus developing a stronger mental state. In computational modelling these effects are achieved by incorporating the effect of Hebbian learning rule (see Caporale and Dan 2008) which describes the plasticity of neural connections.

Mindfulness-based therapy practices have been successfully used for the purpose of coping with stress and various clinical applications to known extent at least since the 2000s (see Kabat-Zinn et al. 1998; Shapiro, Schwartz, and Bonner 1998; Davidson et al. 2003; Segal et al. 2002). Afterwards, the growing body of literature showed importance of these techniques in dealing with extreme emotions by providing supporting empirical evidence (see Farb et al. 2010; Hede 2010; Eberth and Sedlmeier 2012). These techniques include for example the so-called mindfulness-based stress reduction (MBSR) program as described by Kabat-Zinn et al. (1998) and also various yoga and meditation techniques which are very diverse and have been existing long before the stress term appeared (see Jevning, Wallace, and Beidebach

1992; Joshi 2006). The term mindfulness means essentially the self-regulation of ones' attention, including concentration and attention switching. It is considered to be a meta-cognitive skill as practicing mindfulness would require both control of cognitive process (i.e., attention self-regulation) and monitoring the stream of consciousness (see Bishop et al. 2004; Flavell 1979). Although the mindfulness approach itself is often associated with such practices as yoga and meditation, it may be incorporated into various other activities, for instance - autogenic training (see Mohammadi Ziabari and Treur 2018b).

The positive effects mentioned previously were studied for mindfulness and music therapy (see K.S., V.S., and K.G. 2012; Gotink et al. 2018; Modinos, Ormel, and Aleman 2010), indicating the differences with people who do the practice and the people who do not. The topic has been studied exhaustively from the neuroscience perspective to show the underlying neural mechanisms (see Tang, Hölzel, and Posner 2015). Another research in this knowledge domain aimed to study in particular brain areas related to memory, between the people who practice mindfulness regularly over a long time period and people who do not. The result showed significant positive correlation between mindfulness practice and the size of memory related part of the brain, as well as higher performance in episodic and working memory related tasks among people who practice regularly (see Hölzel et al. 2011; Brown et al. 2016). Thus, memory interactions were also addressed and incorporated in the implemented mindfulness simulation, showing the connections between different memory types and other various cognitive states during the therapy practice.

Music in general and music therapy in particular seem to be a more favoured topic for research, as it is simpler to carry out different studies related to brain activity measurements. This is due to the technical aspects of operating such a research. In case of mindfulness, it is indeed possible to make the measurements, but only in a pretest/post-test manner. Unlike the music therapy, where the studied individual may experience listening to music or singing while being monitored at the time. Surely, this depends on the kind of mindfulness therapy which we aim to study, however it makes it more challenging to do while a person is moving as in yoga practice, or needs to be in a certain position, including their ambience, as in meditation. Comparable to mindfulness, music therapy also shown to positively affect memory functions, and have a great potential in neurological rehabilitation, cognitive recovery and prevention of depression as could be seen from work of Särkämö et al. (2008). The effects of music therapy include positive intervention for adults with symptoms of stress, depression, and anxiety (see Hanser 1985). Another research studied these positive effects of music therapy to suppress anxiety in stressful situation for patients undergoing surgical operations (see Steelman 1990), showing that music indeed is a low-cost therapy that has a great potential in reducing not only extreme emotional feelings but also surgical, procedural, acute, and chronic pain (see also Kemper and Danhauer 2005). Also music therapy firmly affects common emotion processing in such areas of the brain as Amygdala, Hippocampus and Orbitofrontal Cortex, as pointed by Koelsch et al. (2013). Generally music therapy appears as a more clear and accessible treatment for people as it has lower entry threshold and the appreciation for music is widely shared within our society. Although the preferences in types of music vary individually and culturally, certain kinds of music occur to have more consistent effects, as showed by McCraty et al. (1998). Thus, we distinguish the persons' reaction for "sad" and "happy" music (see Biller, Olson, and Breen 1974; Khalfa et al. 2008) and also incorporate the effects of singing while listening to music, into the computational model.

Another therapy which is considered in the scope of this research is humour therapy. Humour is essential part of communication in our society, highly valuable for social interaction. The main effect of humor is laughter, which is considered to be the physical expression of its appreciation (see Keith-Spiegel 1972). It helps us to express our positive emotions such as feeling of happiness, excitement and joy. Quantitative research is available on the subject of humour and laughter, related to its effects on human both psychologically and physiologically. Notable use of humour is seen in medicine and education, as detailed greatly by Robinson (1970). Robinson states that although humour is mostly avoided as a communication tool in academia, it may be helpful for students in dealing with stress in their environment. The same research also shows how humour is used in communication between health care professionals and patients in hospitals to subdue anxiety, fear, anger, embarrassment and other feelings associated with stress. Compared to mindfulness, humour therapy similarly to music has a lower entry threshold for the users, and it is commonly spread in our society. Laughter corresponds with release of happiness hormones in the brain - endorphins, which showed efficiency in controlling pain response (see Haig 1988; Weisenberg, Tepper, and Schwarzwald 1995). Additionally, Tse et al. (2010) highlighted its major effects in dealing with chronic pain together with increasing happiness. Overholser (1992) pointed out in his work how humor can be used in life to deal with a variety of stressful situations. He also showed how the efficiency for such experiments might be successfully measured. Positive physiological effects of humour therapy include its impact on muscular, respiratory, circulatory, endocrine, immune, and cardiovascular systems (see Fry Jr 1992; Berk 2001; Wanzer, Booth-Butterfield, and Booth-Butterfield 2005). Thus, both physiological and psychological effects were incorporated in the simulation including for instance lung capacity or abdominal muscle.

Finally, we would like to mention the role of a self-reflection in individual, practicing therapy. More time spent occasionally or periodically on similar therapies, or in other words consistency in the goal to reduce stressful feelings, leads to an increase in therapy effects on a greater scale. As it was pointed earlier, various studies support this hypothesis. In this way, a persons faith in positive effects of a therapy actually enhances the effects, as in placebo effect (see Benedetti et al. 2005). Thus, as one of the major assumptions in the simulation holds, we integrate the impact of positive/negative faith in therapy effects for a user. We also use it as input parameters for the simulation.

3 Software Architecture

3.1 Software Overview

The architecture of the software was designed and implemented following the widespread design patterns such as client-server partitioning and Model-View-Controller (MVC) designation. The client server architecture implies that the client (in our case it is an application GUI) sends requests to the server part (through API made with Java). The server processes request and sends response back to the client, which then communicates it to the user. MVC pattern helps in separating internal information representations from the ways it is interacted with user. The *View* component is presented as front-end GUI. While the back-end has *Models*, which serve as dynamic data structures, and *Controllers*, which maps requests, validates the input data and performs interactions on the data model objects. On Figure 2 the interaction between these components is depicted.

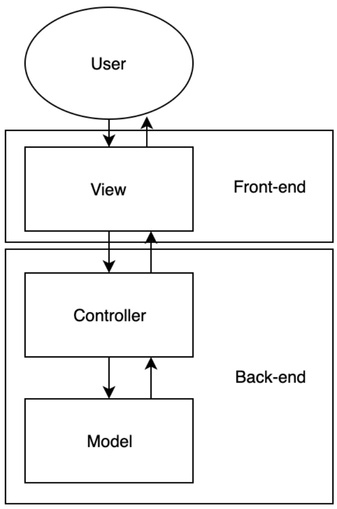

Figure 2. Interaction of software components

We annotated models as Java Persistence API (JPA) entities. JPA is used as a layer that handles the management of relational data in the application by communicating with the database.

During the application designing process, functional and architecturally-significant requirements were first fixed as a starting point, together with use-case diagram as showed below on Figure 3. On the use-case diagram the functionality of the software is depicted from the user perspective as available actions. Each action is shown in a separate ellipse. The order of the actions is depicted using arrows. The loops inside the use-case diagram emphasize continuous actions which may be performed at any time since first usage.

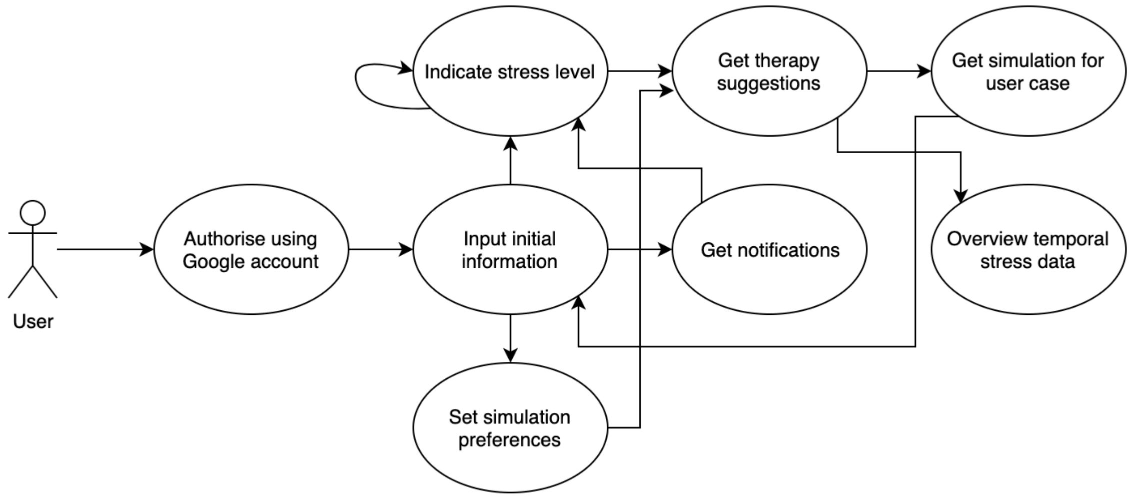

Figure 3. Application use-case diagram for a user

Together with the depicted software architecture (see Figure 4) it makes a correct overview of the implemented software. As of the technological stack for the development, it was concluded to use Java programming language for the back-end server part mainly because it is a current industry standard and there is extensive supporting material available. We used Spring Boot framework for building the server and restful API due to the same reasons, also it runs on Java EE and provides great collections for building web applications. During the discussion on the front-end side stack it was decided to use a Java Script programming language for the GUI as it provides more flexibility over other tools, making it possible to port the resulting front-end across different devices. We used Matlab for the entire computational part of the project as it naturally handles mathematical implementations, computational models and provides powerful optimized vector operations. In addition, recently published Matlab engine API for Java provides a powerful communication layer which simplifies interaction between the two and perfectly suits our implementation case.

As mentioned previously we used client-server software architecture with client being Java Script GUI application on a mobile device and server incorporating restful API, implemented using Java and Spring Boot framework. It is important to note that the Java Script front-end GUI was designed and implemented out of the scope of this paper as it was done by VU Amsterdam students Daniel Kadar and Kamil Aydin.

3.2 Server part and API

The server part is divided as mentioned, following MVC principles. It includes two models being User and Simulation, and corresponding User and Simulation controllers. Thus, these models are used as data entities and the controllers are implementing all the data manipulations through corresponding repositories, as well as they handle mapping of the API calls. Another class implemented next to the models and controllers is the simulation service class which contains all the logic regarding various simulation manipulations, such as suggestion of therapy type or running the simulation. This service when called opens connection to a Matlab Engine Future instance using the Matlab Engine API for Java, then it communicates with the engine by sending data, running commands and receiving the results. All the interaction between Java and Matlab is implemented using asynchronous calls, thus making it possible to run multiple tasks simultaneously. Below on Figure 4 the component diagram is shown, depicting the software architecture as distinct components.

Results of every simulation run and parameter tuning process are saved as a Matlab native binary file, which contains the data in an array form. Also the user input parameters (i.e. initial values for a simulation) are saved in a coma-separated values (csv) format for each simulation run together with the results of simulated annealing process. This allows us to easily check the parameters when there is no need in operating Matlab.

The API on the server has in total nine different method functions implemented, including http GET, PUT and POST methods. The front-end part makes calls to these API methods, server handles the logic and returns result back to the front-end. These methods include data handling for basic user information, their preferences regarding therapy types and current stress situation. Also implemented methods handle running a simulation, getting temporal

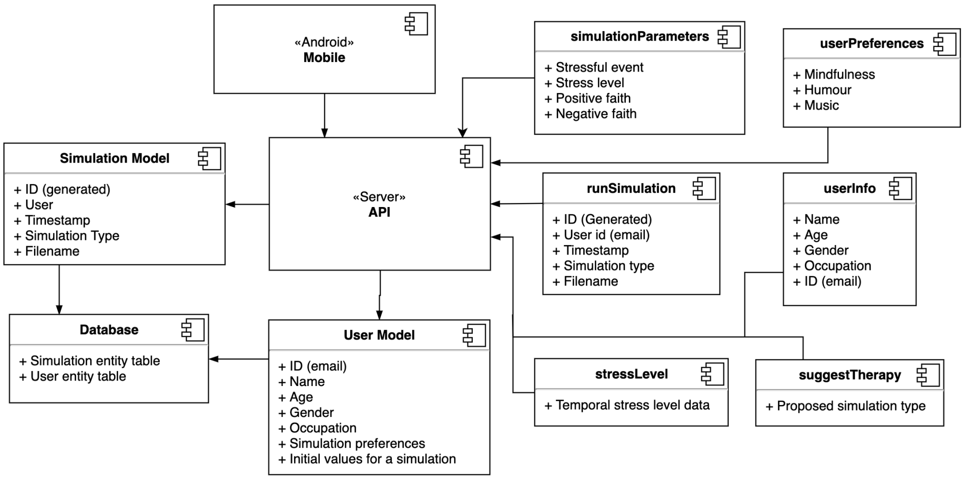

Figure 4. Application component diagram

data with stress level over the recent time period and therapy suggestion method which returns a proposed therapy type for a particular user, taking into account their current situation, previous simulation results and their preferences. Following is the list of all implemented API methods on the server in the form of URL path, including brief description:

GET Methods:

- /userInfo - Returns info for all users available.
- /userInfo/{id} - Returns the info for a user with {id}.
- /stressLevel/{userId} - Returns stress level for the last 14 days for the user with {userId}.
- /suggestTherapy/{userId} - Returns suggestion on the therapy based on previously aggregated user data for a user with {userId}.

PUT Methods:

- /userInfo/{id} - Updates the info of a user (without updating {id}), returns new user data.
- /userPreferences/{id} - Sets simulation preferences for a user with {id}, returns new user data.
- /simulationParameters/{userId} - Sets simulation parameters for a user with {userId}, returns new user data.

POST Methods:

- /userInfo - Saves new user info, returns what's been saved.
- /runSimulation/{userId} - Creates a new simulation and returns simulation for user with {userId}, runs simulation.

For storing relational data, a database has been designed and implemented, containing tables for both previously mentioned entities. For this we used a Java-written H2 database, as it can be simply embedded into a Java application and perfectly fits our research needs without overloading the application. For interaction with the database within the application the JPA was used, creating two repository classes and using the Java annotations to indicate models for both entities. The database architecture is shown on Figure 5 below. The tables in the database have one-to-many connections, meaning that one User may have multiple Simulations connected to them, while a single Simulation is connected to only one User.

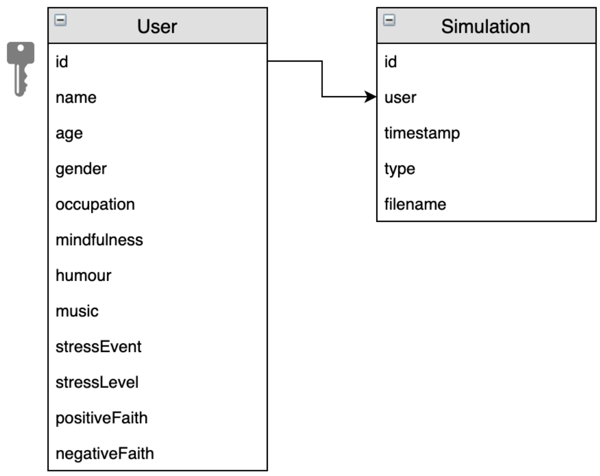

Figure 5. Server database architecture

All the implemented API methods were tested thoroughly and a number or validation techniques were put inside the controller classes. Including checks for existing user while saving new user data, to avoid duplicating entries in the database, as well as in case of a GET call to the API we check if the user with specified id exists in the database. In both cases custom exceptions were made to communicate the check results with the client side. Another implemented checks cover the input data validation, e.g. correct email format for user id.

4 Computational Model

4.1 Model Overview

As it was briefly mentioned previously, computational model implemented for this research is a temporal-causal network model which is based on the Network-Oriented Modelling approach as detailed in the book *Network-Oriented Modeling* (2016). Temporal-causal network models can be portrayed by means of two interchangeable representations: conceptual representation, presented either graphically by a graph or an adjacency matrix; numerical representation, derived in the form of mathematical difference and differential equations. Conceptual representation in the form of a graph is adopted from the Computer Science graph theory. The network graph consists of nodes which speak for cognitive states, and connections between the nodes which represent causal impacts of the states on each other. Each of the states has its *activation level* that changes value over time and represents the dynamics within the network. As in the real world, some states are able to change their values faster than the others. This is reflected in the network by the *speed factors* of the states. In the same manner the strength of a connection between states may be sometimes stronger or weaker, which is handled by the *connection weights*. Furthermore, to aggregate multiple causal impacts on a state from other states, the concept of a *combination function* is used. Thus, the three main components of a Network-Oriented Modelling approach based on the temporal-causal network could be outlined as follows:

- **Speed factor** η_Y of state Y handles the speed of activation change for Y upon impact from X.
- **Connection weight** $\omega_{X,Y}$ of the connection from a state X to a state Y represents the strength of this connection and the impact value that state X has on state Y. This is often in the range $[0,1]$, but sometimes below 0 for a negative effect, or above 1 for a more intense impact.
- **Combination function** $c_Y(...)$ of state Y is chosen for each state in order to aggregate the causal impacts of other states on Y.

Cognitive model of a therapy is built upon a common extreme emotion network adopted from the previous research. It is commonly used as a base for network-oriented modelling on the subject of extreme emotions (see Mohammadi Ziabari and Treur 2018a, 2018b, 2019; Andrianov, Guerriero, and Ziabari 2020). The conceptual graph representation of the common extreme emotion network is shown below on Figure 6. It is considered that first world state of context and extreme emotion occur, which stimulate sensory state and its sensory representation, that is followed then by a feeling of extreme emotion and finally escalating preparation and execution of extreme emotion. The connections within this network are cyclic which makes the activation levels continuous.

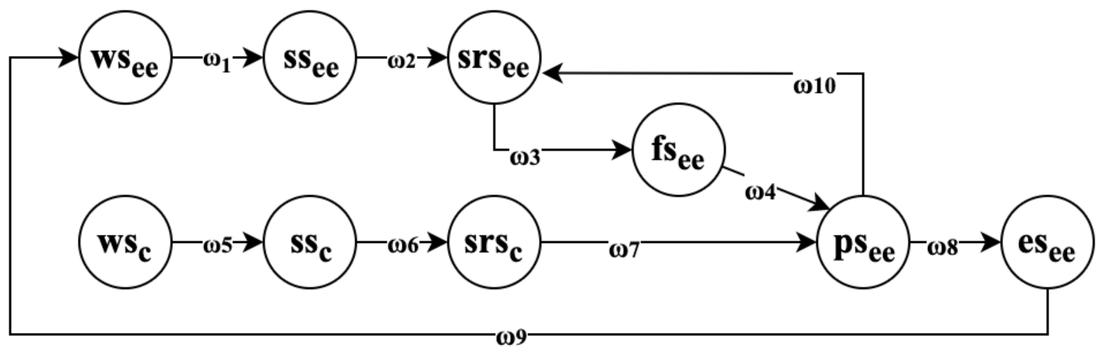

Figure 6. Common extreme emotion network

As described previously, the designed cognitive model of a therapy practice, justifying the states of the network model and their connections based on quantitative literature research in the fields of Psychology, Neurosciences, etc. We repress the preparation and execution states activation in the common extreme emotion network by adding connections to the states, containing negative weight. Thus, we simulate the therapy effects on a person under stress.

An example of such conceptual representation, fully showing the structure of a yoga practice network model could be seen on Figure 7 below. As mentioned previously the effects of mindfulness therapy on different cognitive states in this case are incorporated. The actions in yoga practice are divided into breathing and body movement, which are performed simultaneously, as derived from literature.

The sensory representation of an extreme emotion feeling stimulates the persons' goal to reduce this feeling by means of mindfulness therapy. This triggers the preparation state for practicing, followed by body movement and breathing. Alongside, the effect of a persons

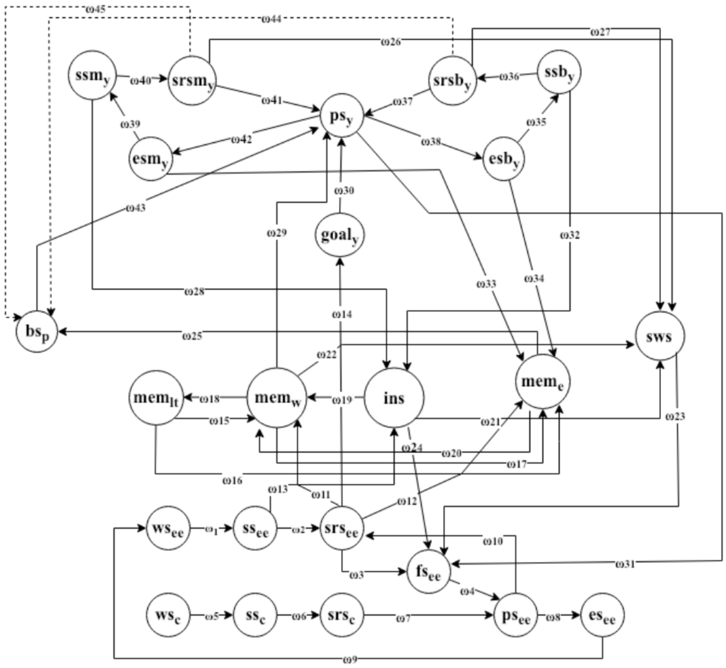

Figure 7. Conceptual representation of mindfulness therapy model (as in Andrianov, Guerriero, and Ziabari 2020)

faith in therapy effects is incorporated, as well as the memory interaction and self-awareness. For the detailed explanation and description of the states, see Andrianov, Guerriero, and Ziabari (2020). Dotted lines represent the adaptive connections, achieved my applying the Hebbian learning rule.

4.2 Numerical Representation

Accordingly to the described approach, the model is first designed at a conceptual level and further transformed into numerical representation. The process of transforming a conceptual representation into a numerical one is detailed in Chapter 2 of the book *Network-Oriented Modeling* (2016). The numerical representation is later used as a basis for the simulation implementation and further mathematical analysis. In this section, the process is described and the the example of numerical representation is shown. The following applies:

- For every time point t in the interval $[0,T]$ with a step δt, each state Y in the model has a real number value of activation level, usually laying in the interval $[0,1]$.

- At each time point t, every state X_i connected to state Y, has an impact on Y, which is defined as $impact_{X_i,Y}(t) = \omega_{X_i,Y} X_i(t)$, where $\omega_{X_i,Y}$ is the connection weight of the connection from X_i to Y.
- The *aggregated impact* of multiple states X_i on Y at a time t is determined using some combination function $c_Y(...)$, such that:

$$aggimpact_Y(t) = c_Y(impact_{X_1,Y}(t), ..., impact_{X_k,Y}(t)) = c_Y(\omega_{X_1,Y} X_1(t), ..., \omega_{X_k,Y} X_k(t)) \tag{4.1}$$

  where X_i are the states connected to Y.
- The effect of $aggimpact_Y(t)$ on Y is exerted over time gradually, depending on speed factor η_Y:

$$Y(t+\Delta t) = Y(t) + \eta_Y [aggimpact_Y(t) - Y(t)]\Delta t \tag{4.2}$$

$$\delta Y(t)/\delta t = \eta_Y [aggimpact_Y(t) - Y(t)] \tag{4.3}$$

- Finally, the following difference and differential equations are obtained for Y, accordingly:

$$Y(t+\Delta t) = Y(t) + \eta_Y [c_Y(\omega_{X_1,Y} X_1(t), ..., \omega_{X_k,Y} X_k(t)) - Y(t)]\Delta t \tag{4.4}$$

$$\delta Y(t)/\delta t = \eta_Y [c_Y(\omega_{X_1,Y} X_1(t), ..., \omega_{X_k,Y} X_k(t)) - Y(t)] \tag{4.5}$$

Combination functions are vary for each application, as various approaches are possible to address the multiple impacts aggregation. Therefore, the Network-Oriented Modelling approach based on temporal-causal networks incorporates for each state a way to specify how multiple causal impacts on this state are aggregated, by means of some combination function. A list of commonly used combination functions are available to achieve the desired outcome (see *Network-Oriented Modeling* 2016, Ch. 2.6 and 2.7). For more customization, a number of parameters for the combination functions are considered. For this research we use computational model which comprehend the following combination functions in order to aggregate multiple impacts. For the states with single impact from only one other state the *identity function* $id(...)$ was used. For states with multiple impacts from other different states, the *scaled sum function* $ssum_\lambda(...)$ with scaling factor λ as a parameter, and the *advanced logistic sum function* $alogistic_{\sigma,\tau}(...)$ with steepness and threshold parameters σ and τ accordingly, were used:

$$id(V) = V \tag{4.6}$$

$$ssum_\lambda(V_1, ..., V_k) = (V_1, ..., V_k)/\lambda \tag{4.7}$$

$$alogistic_{\sigma,\tau}(V_1, ..., V_k) = [1/(1+e^{-\sigma(V_1+...+V_k-\tau)}) - 1/(1+e^{\sigma\tau})](1+e^{-\sigma\tau}) \tag{4.8}$$

For each state and the set of values selected, such as connection weights, speed factors and combination functions for this state, there is a difference and differential equation assigned respectively. Below follow some examples of such difference and differential equations which were used in the model. For the states with single incoming impact and identity function these formulas are:

$$ws_{ee}(t+\Delta t) = ws_{ee} + \eta_{ws_{ee}}[\omega_{es_{ee},ws_{ee}} es_{ee}(t) - ws_{ee}(t)]\Delta t \tag{4.9}$$

$$\delta ws_{ee}(t)/\delta t = \eta_{ws_{ee}}[\omega_{es_{ee},ws_{ee}} es_{ee}(t) - ws_{ee}(t)] \tag{4.10}$$

$$es_{ee}(t+\Delta t) = es_{ee} + \eta_{es_{ee}}[\omega_{ps_{ee},es_{ee}} ps_{ee}(t) - es_{ee}(t)]\Delta t \tag{4.11}$$

$$\delta es_{ee}(t)\delta t = \eta_{es_{ee}}[\omega_{ps_{ee},es_{ee}} ps_{ee}(t) - es_{ee}(t)] \tag{4.12}$$

For the states with multiple impacts from different other states and scaled sum function, advanced logistic function used, these formulas are:

$$srs_{ee}(t+\Delta t) = srs_{ee}(t) + \eta_{srs_{ee}}[(ss_{ee}(t) + ps_{ee}(t))/\lambda - srs_{ee}(t)]\Delta t \tag{4.13}$$

$$\delta srs_{ee}(t)/\delta t = \eta_{srs_{ee}}[(ss_{ee}(t) + ps_{ee}(t))/\lambda - srs_{ee}(t)] \tag{4.14}$$

$$goal(t+\Delta t) = goal(t) + \eta_{goal}[1/(1+e^{-\sigma(srs_{ee}-\tau)}) - 1/(1+e^{\sigma\tau})](1+e^{-\sigma\tau})\Delta t \quad (4.15)$$

$$\delta goal(t)/\delta t = \eta_{goal}[1/(1+e^{-\sigma(srs_{ee}-\tau)}) - 1/(1+e^{\sigma\tau})](1+e^{-\sigma\tau}) \quad (4.16)$$

Above, difference (4.13) and differential (4.14) equations for the sensory representation of extreme emotion state are presented, which among other possible effects influences activation of the goal state. On (4.15) and (4.16) the difference and differential Equations shown for the persons goal state which indicates the intention of a person to suppress extreme emotion by means of therapy practice.

As it was pointed previously, we used adaptivity connections to reflect on the ability of a human nervous system to strengthen neural connections. For this we applied the Hebbian learning rule. In case of mindfulness therapy network these connections are considered to be from the sensory representation of breathing and body movement (srs_b, srs_m) to the positive faith state (bs_p). Similar adaptivity connections take place in other therapy simulations. Thus, simulation shows the ability of a person to maintain positive faith in therapy effects which is then considered to affect the upper boundary for sensory representation and feeling of extreme emotion states activation levels. It is assumed that the connection strength ω for these states is adapted using the Hebbian learning rule, accounting a learning rate $\eta > 0$ and a persistence factor $\mu >= 0$ with activation levels $X_1(t)$ and $X_2(t)$ of the states involved. Thus, we get the following differential and difference equations for mindfulness therapy:

$$\omega(t+\Delta t) = \omega(t) + \eta[srs_m(t)bs_p(t)(1-\omega(t)) - (1-\mu)\omega(t)]\Delta t \quad (4.17)$$

$$\delta\omega(t)/\delta t = \eta[srs_m(t)bs_p(t)(1-\omega(t)) - (1-\mu)\omega(t)] \quad (4.18)$$

$$\omega(t+\Delta t) = \omega(t) + \eta[srs_b(t)bs_p(t)(1-\omega(t)) - (1-\mu)\omega(t)]\Delta t \quad (4.19)$$

$$\delta\omega(t)/\delta t = \eta[srs_b(t)bs_p(t)(1-\omega(t)) - (1-\mu)\omega(t)] \quad (4.20)$$

4.3 Model Verification

Finalizing this chapter, we would like to acknowledge possible actions in order to carry verification of the computational model and confirm its mathematical accuracy. As defined in the book (see *Network-Oriented Modeling* 2016, Ch. 12), a state Y of the model has a *stationary point* at time t if the conditions holds $\delta Y/\delta t = 0$. The model is considered to reach its equilibrium at time t if every state Y_i of the model has a stationary point at t. More specifically, in a temporal-causal network model the following criteria for having a stationary point can be found:

$$c_Y(\omega_{X_1,Y}X_1(t),...,\omega_{X_k,Y}X_k(t)) = Y(t) \tag{4.21}$$

Here X_i are the states with connection to state Y, and $c_Y(...)$ is the combination function for Y. For instance, stationary point equations for the scaled sum function and the advanced logistic sum function used in the mindfulness therapy are the following:

$$srs_{ee}(t) = ssum_{\lambda}(\omega_{ss_{ee},srs_{ee}}ss_{ee}(t), \omega_{ps_{ee},srs_{ee}}ps_{ee}(t)) \tag{4.22}$$

$$goal(t) = alogistic_{\sigma,\tau}(\omega_{srs_{ee},goal}srs_{ee}(t)) \tag{4.23}$$

These criteria need to be checked for stationary points found by substitution of the values obtained in the simulation and calculated the deviation. For the purposes of validation no numerical empirical data were available. Thus, quantitative information from the literature of previous researches has been used to analyse expected behaviour patterns and test the model. Furthermore, as mentioned previously, the empirical data gathered with the developed integrative model software will be further used for the purpose of model validation and improvement.

5 Parameters Tuning

5.1 Simulated annealing

In order to make the outcome of the model individual for every user, we use parameter tuning process. Bound constrained minimization is used for this purpose by means of simulated annealing. This method is an adaptation of pre-existed Monte Carlo methods, its name comes from annealing in metallurgy, a technique involving heating and controlled cooling of a material to improve its form and reduce defects. The simulation of annealing can be used to find an approximation of a global minimum for a function with a large number of variables (see Khachaturyan, Semenovsovskaya, and Vainshtein 1981).

First, we make an initial run of the generalized model. If the parameters tuning is on for a user, we run simulated annealing for the general model, with unknown speed factors as variables for the optimization. Simulated annealing is computed with the objective function which returns the scalar value of the objective function. The objective function sum of squared residuals (SSR) is calculated based on deviations of the model values from the empirical data (Equation 5.1), in our case result of the generalized model.

$$SSR = \sum_{i=1}^{N} (Y(t_i) - X(t_i))^2 \tag{5.1}$$

Where Y_i is the empirical data sample and X_i is the value predicted by the model. After the SSR calculation we use root mean square (RMS) equation (5.2) in order to take the mean of previous calculations.

$$RMS = \sqrt{\frac{SSR}{N}} = \sqrt{\frac{(X(t_1) - Y(t_1))^2 + ... + (X(t_N) - Y(t_N))^2}{N}} \tag{5.2}$$

The simulated annealing algorithm generates an arbitrary trial point and chooses the distance of the trial point from the current point by a probability distribution with a scale depending on the current temperature. We used fast annealing with step length equals the current temperature, and direction distributed uniformly random. After generating the trial point, the algorithm moves the point in order to find extremum of the function. As previously mentioned we set upper and lower boundaries in the range $[0.05, 0.9]$ for the algorithm to lower the number of iterations and reduce computation time. The algorithm chosen trial points are uniformly distributed at random, incorporating value at the each iteration. Algorithm periodically lowers the temperature and stores the best point found to this moment. Iterations stop when the average change in the objective function is small relative to set up function tolerance. We used common tolerance value of 1×10^{-6} and the default acceptance function (see Equation 5.3) for new points. See the work of Ingber (1996) for a more detailed description of this algorithm.

$$\frac{1}{1 + e^{\frac{\Delta}{max(T_0, T)}}} \tag{5.3}$$

Where Δ is the difference between objectives, T - initial and current temperature. In our case we also include another stopping criteria by limiting the maximum computational time and setting upper boundary to 90 minutes. If the computation is not finished after 90 minutes, we get values from the best iteration. Currently the optimization function is set up with 3 variables. This decision was made after an experimental run. Initially, running the simulated annealing algorithm with the indicated objective function and all speed factors of a model as variables took more than 12 hours and was not done at that moment. Thus, we continued the experiments with decreasing the number of variables and concluded to use speed factors of 3 key states as variables for the optimization problem. The time boundary is set to 90 minutes by cause of experimental run for 5 states which took more than 2 hours to compute. Currently the 3 states considered are ws_{ee}, fs_{ee} and es_{ee}, which represent world state for extreme emotion, feeling and execution states for extreme emotion respectively.

Although, the simulation tuning part was implemented using threads and asynchronous computations, it does not provide the sufficient level of parallelism needed for a more efficient computation. However, this is based on the carried experiments, which took place using a compact laptop, and the result might differ for a run on more powerful machine. We see possible adjustment in pre-allocation of some arrays which are currently changing size dynamically each iteration, this could decrease the calculation time. Another possible improvement point for this process is to implement optimization with various other algorithms such as gradient boosting/stochastic gradient descent to compare performance and find the best method experimentally. Gradient descent usage might be more favourable in case where high performance computing (HPC) is unavailable, since it could more efficiently find local optimum of a function rather than simulated annealing, which is more suited for the global optimum calculation.

5.2 Exponential Moving Average

As it was pointed earlier, we set up a minimum number of recent simulations in order to turn on the parameter tuning part. Thus, to normalize the data we start optimizing the model output when at least 5 simulations took place. Prior to each simulation run, the number of recent simulations is indicated to make a decision on applying parameter tuning and averaging or not. This process is done both for the user input simulation parameters, such as stress level, positive faith, etc., and for the results of simulated annealing. For this purpose we use exponential moving average (EMA) in order to normalize these values and achieve a smoother function behaviour. Below this formula (5.4) for the simulated annealing results is presented:

$$EMA_i = (\eta_Y - EMA_{i-1}) * (\frac{2}{N} + 1) + EMA_{i-1} \tag{5.4}$$

Where N is the number of recent simulations to take into account, and η_Y is the speed factor which is used as variable for simulated annealing. EMA, which is also known as an exponentially weighted moving average (EWMA) is a weighted form of moving average. It serves as an infinite impulse response (IIR) filter, applying weighting factors which decrease exponentially. Using the averaging allows us to smooth out short-term fluctuation dynamics and highlight more long-term patterns in the data, avoiding extreme situations. Number of previous values to take into account for the initial value depends on user input data. Large deviations in the input will affect the total, even for a considerably small weight. We presume the input to change gradually, and not to have great variations over time, thus we consider 5 recent simulations for averaging.

6 Ambient application and simulation outcomes

Incorporating the components which were described in previous chapter, we can draw a detailed diagram for the ambient application to illustrate the process inside the implemented software. Below on Figure 8 you can see the resulting diagram which consists of three main components: analysis, support and adaptation.

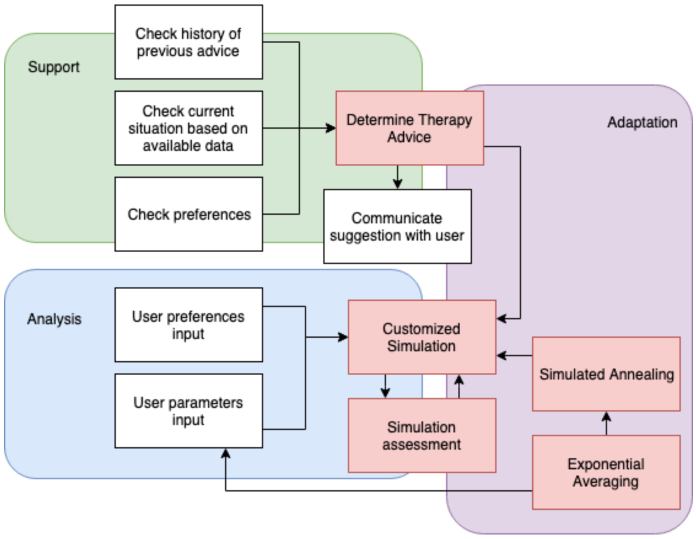

Figure 8. In-depth ambient application diagram

Red boxes represent important features inside the application while white boxes indicate minor steps. Support model is in green colour, it includes checking the agents current situation based on previous input, their preferences and history of previous support decisions in order to determine a suitable therapy. The analysis model is coloured with blue, it validates user input and prepares data for the domain model, it also includes assessment of simulation results. Purple colour is chosen for the adaptation model, which consists of simulated annealing, exponential averaging and also customization of the generalized domain model. Here relation between all sub-components is demonstrated using arrows, the direction of arrows shows how different parts influence each other (e.g. parameter tuning with simulated annealing directly affects the customization of simulation for a user). Clear differentiation of adaptation model is difficult as it also shares common parts with two other models. The process inside depicted ambient application goes as follows: first user enters their preferences and answer questions regarding current situation for the analysis; next the therapy type is determined based on available data, which is then used for current user; prior to starting a simulation, parameter tuning process is applied along with averaging to adapt the simulation; finally, simulation assessment is made after the simulation run to determine its effectiveness.

On Figure 9 the simulation outcomes are present for a person with mindfulness therapy type. The upper graph corresponds to a generalized simulation, while on the bottom we see this simulation after the adaptation process for a particular use-case.

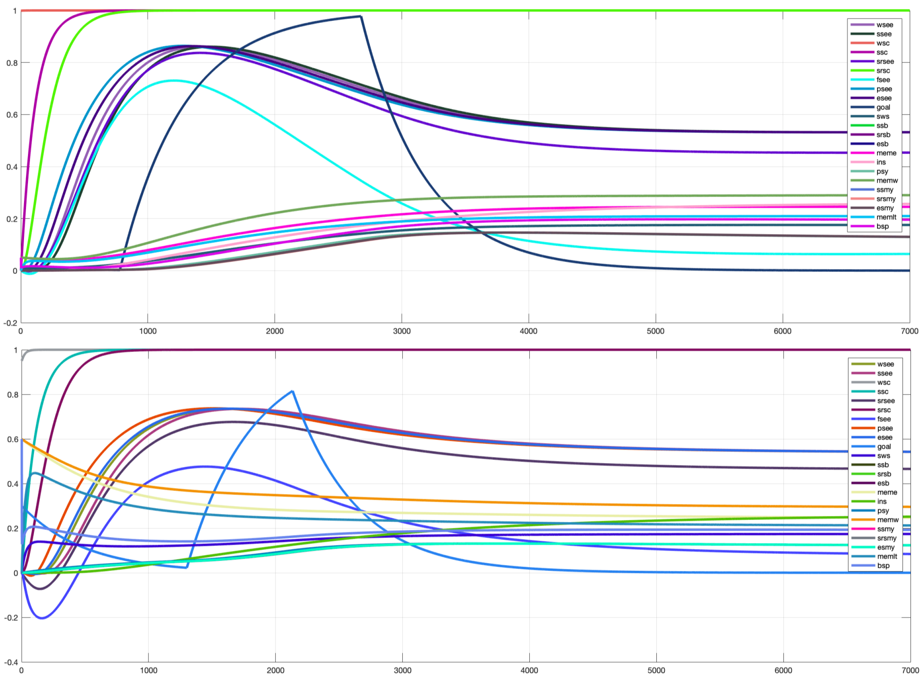

Figure 9. Simulation outcomes before and after adaptation

X-axis indicates the time, Y-axis corresponds to the activation level for a state in the network. The test simulation was made for a user with a higher level of confidence in therapy results and higher persistence in their goal. As we can see the adaptation process alters the results of a simulation to make it more appropriate for this user. Namely, we can notice how the feeling of extreme emotion does not escalate as quickly and has more suppression in the beginning, the goal state for a therapy practice is also affected, as it seems to be less urgent in this case. Overall pattern for the extreme emotion community in the network clearly shows more smooth behaviour and has a lower peak as if the person has developed some resistance for the extreme emotion.

7 Discussion

The initial objective of the project was to develop an integrative model incorporating analysis, support and adaptation parts. The client-server architecture software which has been designed and developed completely fulfills this objective. It includes server part with embedded Matlab interaction and API for client communication. The final version of the software meets all architecturally-significant requirements which were set in the beginning. Prior to the simulation and software development, numerous supportive literature and previous research have been studied exhaustively, main points of interest in design process and development have been described in previous chapters. The goal of the final application to serve as an interface for user interaction with the model, along with gathering empirical data to support further research has been achieved. Discussing the limitations of this work, first of all we would like to point out the computational time for the simulation and parameter tuning part - as it was mentioned previously in order to achieve the greater efficiency for the algorithms, its worth considering usage of other HPC techniques apart from threading and asynchronous calls used in the scope of this research. Currently, parallel execution is only feasible for about $\sim 15-20\%$ of the code, increasing this number may lead to a significant improvement in performance. However, this needs to be done together with hardware-level parallelism such as distributed computing, to achieve the best outcome. Thus, the results of the optimized simulation output heavily depend on the amount of variables and parameters for the simulation process which in turn define individualistic outcome of a simulation. Another limitation was specified previously, as the evaluation of individuals' current state is done by themselves, it implies subjective nature of this data which might not be entirely trustworthy and may entail the so-called self-report bias. Results of this research open up numerous possibilities for further studies as the implemented piece of software may be further used to study the effects of various therapies on stressed individuals. The integrative model may be enriched with empirical data which is gathered during the process in order to provide more progressive simulation results. Furthermore, the computational model of mindfulness therapy might be adjusted based on the observations from these data.

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