A System Dynamics View of Stress: Towards Human-Factor Modelling for Computer Agents

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Abstract. Human factor models are important for computer systems to i) make such systems more human aware (ie. better calculations of human behavior) and ii) make such systems demonstrate more realistic human behaviors (ie. display more human-like AI). Having these capabilities is beneficial in that they allow for technologies that are better aligned with the human social context in which the technology ultimately resides. However, human factor calculations are difficult to quantify, validate, and encode because human behavior is both fuzzy and complex. This paper applies system dynamics, a modelling technique for understanding complex systems, to human factors. It is a way that is computationally useful, and may be validated by experts in human studies. We first model stress as a causal loop diagram, and stock/flow diagram for use as "mental models" in computer programs, agent systems, and simulations.

1 Motivation: Enhancing Agent Systems with Human-Factor Intelligence

> *"The failure of large complex systems to meet their deadlines, costs, and stakeholder expectations are not, by and large, failures of technology. Rather, these...fail because they do not recognize the social and organizational complexity of the environment in which the systems are deployed. The consequences of this are unstable requirements, poor systems design and user interfaces that are inefficient and ineffective."* - Baxter and Sommerville, [1]

According to lead research in socio-technical systems (see [2] for a survey), neglecting social and organizational complexity can cause large, and often serious, technological failures, especially where computer systems are concerned. This is a result of a growing gap between technology and the social need that technology serves. According to Vicente, [3], rapid advances in today's technological systems have made such systems less human friendly, and difficult to control or understand from several perspectives (namely physical, psychological, social/team, organizational, and political domains). Recognizing these needs for "Human-tech" friendly systems, in this case computer systems, is an important step in a wide variety of applications, whether for simulations, interfaces, or other programs. One way to bridge this socio-technical gap is to provide computer programs with cognitive models of human factors like stress, burnout, emotion, trust, personality, leadership, expertise, or decision making ability. There are two main benefits that such human factor enhanced systems would have. First they would be able to be more human-aware, and second they would be able to be more human-like.

1.1 Human-Factor Intelligence in Computer Systems

A more "human-aware" system, by the addition of a human-factor module, would be able to interface with real people in an improved way. For instance applications that must present sensitive information to a user under stressful situations may calculate an optimum level of information display for that user based on its prediction of the user's level of stress. A wireless body area network application, for instance, could provide this information display control program with key data about the user's state that can be combined with knowledge of how stress works. This kind of usage bridges the gap between a computer system and user with cognitive mental maps; just as humans have mental models of how the systems they use operate, the system itself could benefit by having a mental model of its user. This notion of balancing mental models is suggested by Leveson, et al, in the safety science community where they focus on system theoretic accident modelling, for instance, although they steer away from focusing on fuzzy human-factors, [4].

More "human-like" computer systems, through the addition of human factor modules, would be able add a more subjective domain to typical artificial intelligence that could provide increased realism in its varied applications. In particular agent programs based on a deliberative architecture, such as the popular belief-desire-intention (BDI) framework, [5], [6], could make use of human factor models in both single and multi-agent situations. For instance, simulating organizations for emergency response, or crisis management could benefit by having agents that more closely reflect human complexity in their environments. This would mean that the results of such simulations would incorporate a new dimension. This is particularly important for projects which use organization simulation as a means of validating corporate policies, and business processes. A more complex agent more accurately represents human complex agents. A further application could involve the study of human-agent interaction (HAI); a relatively new concept, [7], [8], [9] where humans must work in concert with agent programs to achieve a shared objective. An example domain for this would be 3D gaming environments or virtual worlds such as SecondLife, or World of Warcraft, where virtual agents can interact with human-driven avatars, making for interesting studies in this area.

1.2 Problem: Capturing Human-Factor Intelligence

In either case there is an underlying problem; these human factors are notoriously fuzzy, and are not easily standardized or computable, as is needed for programming purposes. How to make such models quantifiable and computable is an open research problem, and is the focus of this paper. The human factor of stress is selected as the first of several to be modeled and eventually implemented into computer programs. In doing so, definitions from the literature involving psychological studies from the University of Toronto, [10], [11], [12], [13], and definitions from Hobfoll, [14], are extracted and used to begin the models. Validation of human-factor models by experts (in psychology, sociology, economics, mathematics, etc) is highly important, especially considering the vast literature on any human factor. Global standard definitions that are concrete, and agreed upon are difficult to find yet critical to the production of computable human factor models that have actual explanatory power, where human behavior is concerned.

The remainder of this paper looks at an approach to producing a model of stress that is computable. Section 2 discusses the system dynamics tools and methodology for complex system study. Section 3 describes a system dynamics model of stress and coping behavior, including design decisions, causal loop diagrams, and stocks/flows. Section 4 presents the output of this stress model. Section 5 provides a brief discussion and conclusion.

2 System Dynamics

System Dynamics is a methodology and set of modelling tools to describe and understand the seemingly complex and "counter-intuitive behavior of systems", [15], which may be social, technical, or otherwise. The field was pioneered by the early work of Jay Forrester, at the MIT school of management in the forties, and has since grown into a respected discipline that promotes systems thinking as a core concept. It has been used as a principle method in many varied studies, such as climate monitoring, economical forecasting, predicting social trends like technology adoption, market saturation, and predicting changes in population versus urban sprawl, etc (see [16] for more). Its results are well established and flexible for many such complex systems and display high predictive value of actual system behavior. From a managerial perspective, system dynamic models are also easy to explain, and intuitive; an important asset when it comes to discussing complex system behavior with experts and non-experts. Its diagrams have high explanatory value for the systems they model, and are computable, with a strong mathematical foundation. This means that system dynamics models are good for translating into or use within computer programs. Furthermore, there are a number of tools available for both modelling and simulation in system dynamics, two of which have been used in this paper.

2.1 System Dynamics Components

As a method System Dynamics is composed of two primary components that aid in the understanding of systems, namely the use of the causal loop diagram, and the stocks and flows diagram. Causal loop diagramming describes a system in terms of the causal relationships among its components, which may be tangible, or intangible, as in supply chain management, [17]; this all means system dynamics can describe notions that are inherently "fuzzy" such as human-factors and behaviors in terms of their causes. Further the causal loop diagram, as seen in figure 1 below, can be used to explore the overall result of behavioral loops in a system, and hence explain behavior.

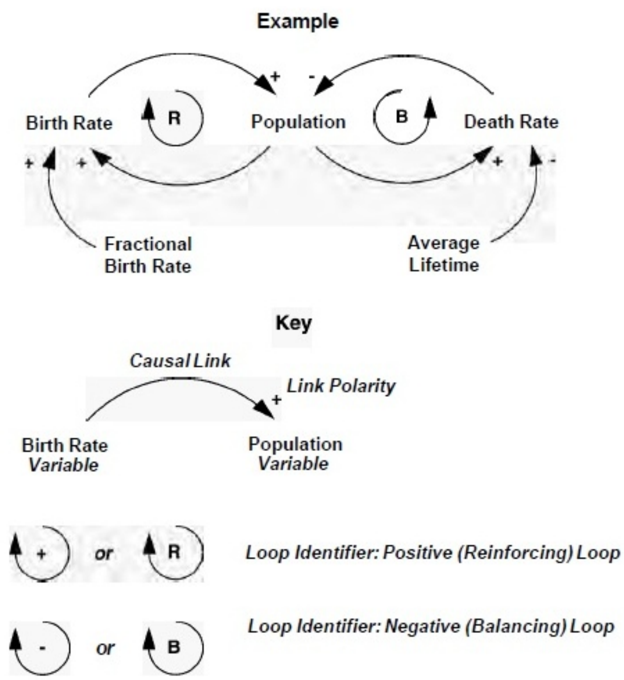

Fig. 1. A causal loop diagram showing behavioral loops. A balancing loop (B) stabilizes a component of the system while a reinforcing loop (R) escalates such a component's behavior. Image taken from chapter 5 of [16] for more.

A stock and flows diagram, on the other hand builds off of its causal loop counterpart by providing quantification of key components in the system. A stock represents a feature of the system that tracks the level or quantity of a certain item in the system. Stocks are like wells or collections that can build up, or diminish over time. The building up or diminishing of a stock is called a flow, representing the transfer of units into or out of the stock. Flows can connect stocks together if the units are the same (or these can be used in equations according to established formulas of rates of change, or constant values that depend on the stock and its flows into either another stock, or a sink. The combination of levels, rates, and constant values allow for taking a causal diagram and translating it into a quantifiable entity. See figure 2 for more details about this. This diagram allows researchers to visualize the system over time, in simulated activity, under varied conditions (by changing equations and the initial values of the levels, rates, and constants).

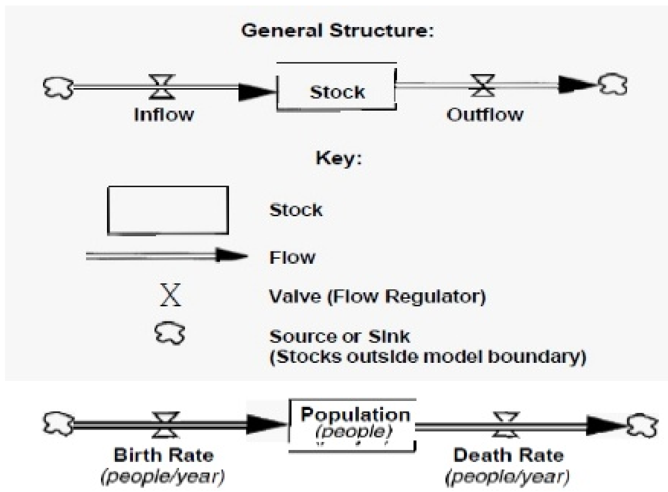

Fig. 2. A stock and flows diagram showing the levels, rates, etc, which describe a component's behavior through equations, and an example of population flow. Image taken from chapter 6 of [16] for more.

2.2 System Dynamics Software Tools

As mentioned, there are a number of special purpose software applications available for system dynamics modelling and simulation. These typically allow for constructing the causal loop and stock and flow diagrams described previously. In addition they usually output the system behavior as a graph showing the behavior of system variables over time. A selection of these tools may be found online in [18]. After a survey of available tools this work has selected Simtegra's MapSys 3.0, [19], for causal loop diagramming (see figures 3 and 4), and SimGua, [20], for stock and flows models, and simulation charts (see figures 5, 6, 7, and 8). The Mapsys tool has powerful causal loop diagramming functionality, while the SimGua tool specializes in stock and flow tools, graphs and, more importantly, the ability to write code in addition to basic equations (thus making it very useful for future integration with customized programs).

3 System Dynamics of Stress

The previous sections gave a motivation for adding human-factors to computer programs, and introduced system dynamics as a modelling paradigm of choice for representing fuzzy human-factors concepts. Stress, is the subject of this section, and below is presented a definition of stress gleaned from literature in the psychology domain, and a proposed system dynamics model based on this literature.

3.1 Stress Definitions

The following terms all relate to factors of stress and have been derived from research papers from the University of Toronto, [10], [11], [12], [13], as mentioned previously, as well as the work by Hobfoll, [14]. Table 1 shows these definitions in a concise format.

Table 1. Definitions used in the proposed model of stress.

Num	Ref	Item Name	Definition
1	3	Stress	The relation between perceived demand and perceived resources.
2	3a	Eustress	The state when perceived demand does not exceed perceived resources.
3	3b	Distress	The state when perceived demand exceeds perceived resources.
4	1	Demand	A stimulus requiring a response action.
5	2	Resource	An entity required in order to perform a response action.
6		Coping Style	A mechanism used to respond to distress.
7	4	Action-oriented Coping	A coping style that minimizes distress through a response action.
8	7	Emotion-oriented Coping	A coping style that minimizes distress by managing emotions.
9	5	Avoidant-oriented Coping	A coping style that minimizes distress by delaying a response action.
10	8	Emotional Stability	The degree to which one's emotional state increases or reduces distress (or eustress).
11	14	Biological Stability	The degree to which one's biological state increases or reduces distress (or eustress).
12	15	Cognitive Stability	The degree to which one's cognitive state increases or reduces distress (or eustress).
13	6	Response Action	An action taken to address a stimulus using available resources.
14	11	Positive Locus of Control	A perception that outcomes are controlled by one's internal abilities.
15	12	Negative Locus of Control	A perception that outcomes are controlled by factors external to the individual.
16	9	Cortisol	A chemical in the body that is correlated with increases in anxiety.
17	13	Heart Rate	A physical parameter associated with increased levels of stress that affects biological stability.
18	10	Anxiety	An emotion that is associated with increased cortisol levels and affects emotional stability.

3.2 Causal Loop Diagrams of Stress

Causal loop diagrams are an effective method for capturing the relationship between inherently fuzzy concepts, like the ones recently defined for stress. Rather than having to precisely describe these relationships, these diagrams allow directed arcs, which represent relationships, to be labelled in terms of the correlation between two concepts. Concepts that are positively correlated (i.e., when one increases or decreases so does the other) are represented with a "+" sign, while concepts that are negatively correlated (i.e., when one increases or decreases the other does the opposite) are represented with a "-" sign. It is exactly this high-level, intuitive representation that makes causal loop diagrams so effective at representing human factors.

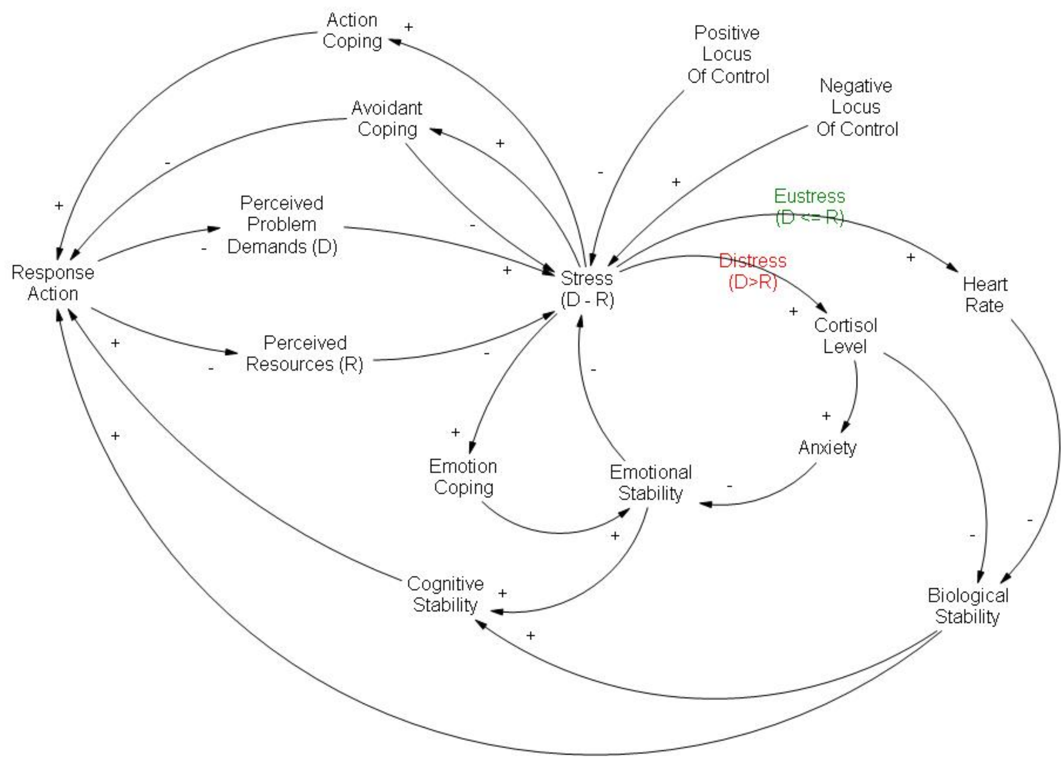

Fig. 3. A causal loop diagram for stress.

In figure 3, our causal loop diagram for stress is shown. This diagram consists of 17 separate feedback loops that impact stress. Some of these loops reinforce stress (i.e., they are positively correlated with stress), while others balance stress (i.e., they are negatively correlated with stress). Each of these loops is labelled and described in table 2 below.

A slightly more in-depth causal loop diagram for stress is shown in figure 4. In it the various feedback loops are labelled as being either reinforcement (R) or balancing (B) loops. This diagram also incorporates delays, which are represented as two short parallel lines that intersect the middle of an arc. Delays add expressivity to the diagram as the effects of time can now be included. If no delay is present on an arc, then the correlative effect of one concept immediately impacts the other. Such is the case between Anxiety and Emotional Stability: as Anxiety increases, Emotional Stability decreases immediately; and as Anxiety decreases, Emotional Stability increases immediately. In our model, an arc with-

Table 2. Feedback loops in the model are shown in the table below. Note there are slightly more balancing than reinforcing loops.

Num	Name	Loop (from Stress)	Description	Effect on Stress
1	Action Coping Loop 1	3,4,6,1,3	As stress increases so too does the action coping mechanism, which results in a response action being taken, which reduces demand and in turn reduces stress.	Balancing
2	Action Coping Loop 2	3,4,6,2,3	As stress increases so too does the action coping mechanism, which results in a response action being taken, which reduces resources and in turn increases stress.	Reinforcing
3	Avoidant Coping Loop 1	3,5,3	As stress increases so too does the avoidant coping mechanism, which in turn reduces stress.	Balancing
4	Avoidant Coping Loop 2	3,5,6,1,3	As stress increases so too does the avoidant coping mechanism, which, over time, results in no action being taken, which does not reduce the demands and does not address the cause of the stress. Hence stress remains reinforced.	Reinforcing
5	Avoidant Coping Loop 3	3,5,6,2,3	As stress increases so too does the avoidant coping mechanism, which, over time, results in no action being taken, which does not reduce the resources or increase stress.	Balancing
6	Emotion Coping Loop 1	3,7,8,3	As stress increases so too does the emotion coping mechanism, which, over time, increases the emotional stability, which in turn reduces stress.	Balancing
7	Emotion Coping Loop 2	3,7,8,15,6,1,3	As stress increases so too does the emotion coping mechanism, which, over time, increases the emotional stability, which increases the cognitive stability, resulting in more response actions, which decreases the demand and in turn reduces stress.	Balancing
8	Emotion Coping Loop 3	3,7,8,15,6,2,3	As stress increases so too does the emotion coping mechanism, which, over time, increases the emotional stability, which increases the cognitive stability, resulting in more response actions, which decreases the resources and in turn increases stress.	Reinforcing
9	Cortisol Feedback Loop 1	3,9,10,8,3	As distress (demand > resources) increases, over time, so too does the cortisol level, which in turn increases anxiety, which decreases emotion stability, and increases stress.	Reinforcing
10	Cortisol Feedback Loop 2	3,9,10,8,15,6,1,3	As distress (demand > resources) increases, over time, so too does the cortisol level, which in turn increases anxiety, which decreases emotion stability, decreasing cognitive stability and reducing the response action, which will result in demand not being addressed, which ultimately increases stress.	Balancing
11	Cortisol Feedback Loop 3	3,9,10,8,15,6,2,3	As distress (demand > resources) increases, over time, so too does the cortisol level, which in turn increases anxiety, which decreases emotion stability, decreasing cognitive stability and reducing the response action, which will result in resources not being used, which will reduce stress.	Balancing
12	Cortisol Feedback Loop 4	3,9,14,15,6,1,3	As distress (demand > resources) increases, over time, so too does the cortisol level, which in turn decreases biological stability, which, over time, decreases cognitive stability and reduces the response action, resulting in demand not being addressed, which ultimately increases stress.	Reinforcing
13	Cortisol Feedback Loop 5	3,9,14,15,6,2,3	As distress (demand > resources) increases, over time, so too does the cortisol level, which in turn decreases biological stability, which, over time, decreases cognitive stability and reduces the response action, resulting in resources not being used, which will reduce stress.	Balancing
14	Heart Rate Feedback Loop 1	3,13,14,6,1,3	As stress increases (either distress or eustress), over time, heart rate will increase as well as response action, and will in turn increase demand and stress.	Reinforcing
15	Heart Rate Feedback Loop 2	3,13,14,6,2,3	As stress increases (either distress or eustress), over time, heart rate will increase as well as response action, and will in turn increase resources, but decrease stress.	Balancing
16	Heart Rate Feedback Loop 3	3,13,14,15,6,1,3	As stress increases (either distress or eustress), over time, heart rate will increase and biological stability will decrease, which, over time, will reduce cognitive stability and response action, and will in turn increase demand and stress.	Reinforcing
17	Heart Rate Feedback Loop 4	3,13,14,15,6,2,3	As stress increases (either distress or eustress), over time, heart rate will increase and biological stability will decrease, which, over time, will reduce cognitive stability and response action, and will in turn increase resources, but decrease stress.	Balancing

out a delay means that time is negligible with regard to one concept's impact on another. However, as is the case between Emotion Coping and Emotional Stability, if a delay is present, it means that the correlative effect is not immediately applied. For example, when an agent begins coping with its emotions (i.e., increasing Emotion Coping), only after a certain period of time (delay) will its Emotional Stability increase (positive correlation). Again, the diagram does not require precision with regard to the exact length of the delay. It is enough that the importance or unimportance of time for the correlative relation is capable of being expressed.

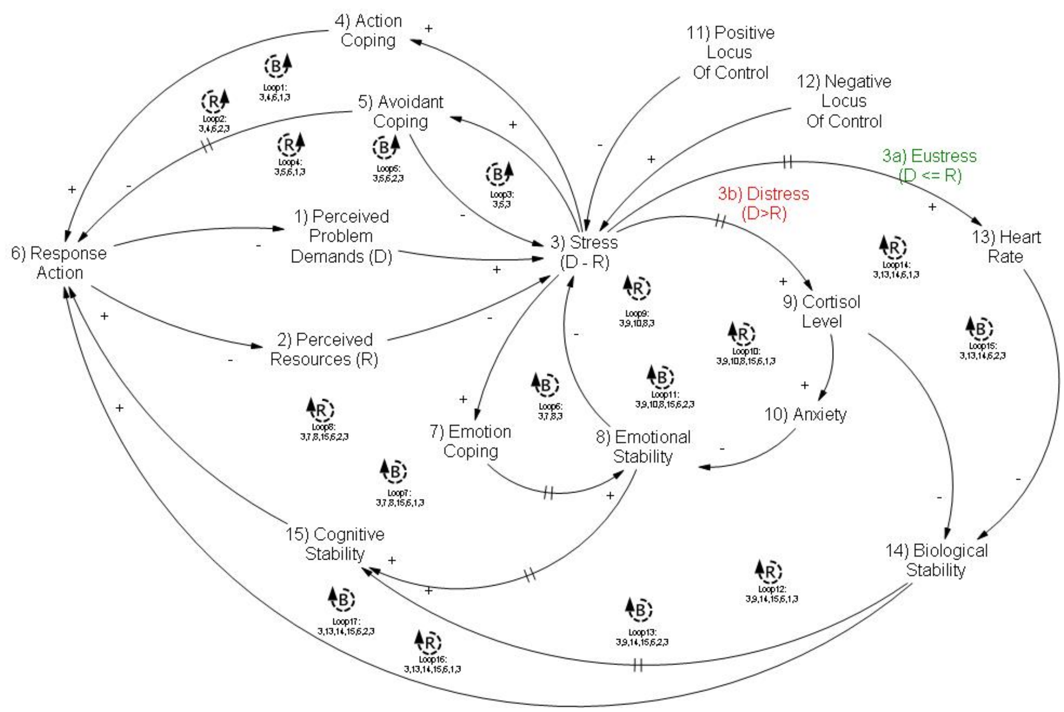

Fig. 4. A more in-depth causal loop diagram of stress showing delays and feedback loops that balance or reinforce stress.

3.3 Stock and Flow Diagram of Stress

Stocks and flows are a first step towards simulation in System Dynamics, and this section describes how this is designed for the stress model defined previously. Stress is primarily focused on the relationship between perceived demand versus perceived resources. This relationship is influenced by other factors that are networked, according to the causal loop diagram described above. Translating these notions into the stock and flow terminology of system dynamics there are six main stocks and flows that are networked according to several important parameters. These stocks are in terms of Demand, Resource, Stress, Positive Emotion, Cortisol, and Heart Rate. The flows increase or decrease the levels of these stocks using varied parameters, as seen in figure 5 below.

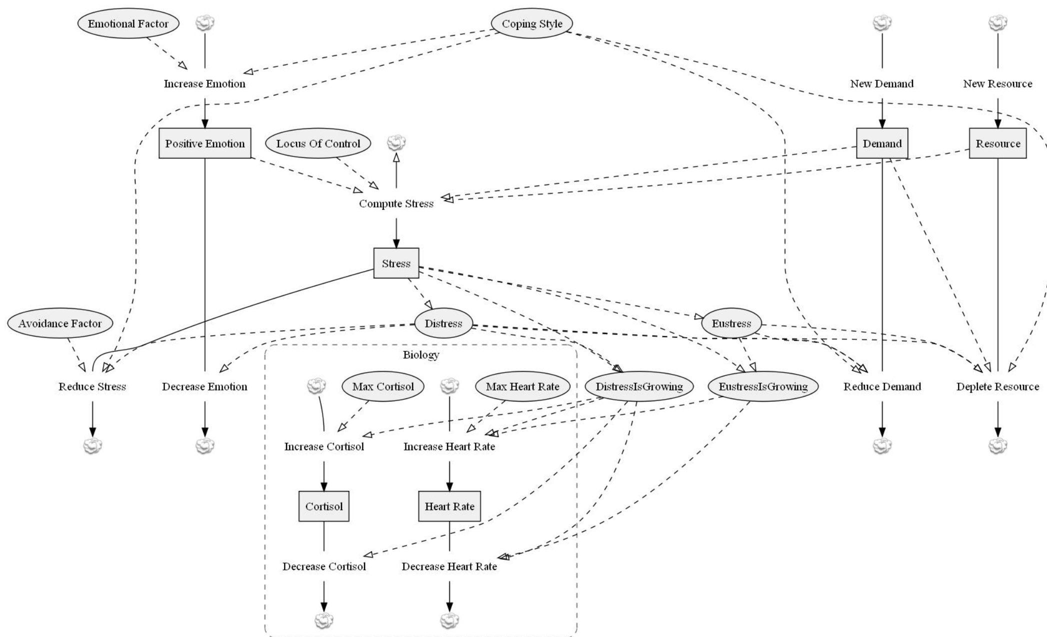

Fig. 5. A stocks and flow diagram of stress, modelled in SimGua, [20].

In this version of the stock and flow diagram the first thing to notice is the use of the coping style parameter, which represents the three styles of coping as three discrete variables which have an influence on various flow computations. This is an early design decision that investigates the behavior of each style of coping independent of the other. In the context of the causal loop diagram earlier, the three styles may be occurring at the same time in the same individual, which is congruent to realistic behavior. In future iterations this will be addressed, however here they are quantified separately according the setting of the Coping Style parameter of figure 5.

1. **Task Oriented Coping** represents taking a response action through using a resource to reduce a demand. Response actions (seen in figure 3) are considered as a result of resource depletion and demand reduction formulas.

2. **Emotion Oriented Coping** factors into the well of positive emotion that contributes to an individual's emotional stability level.
3. **Avoidance Oriented Coping** is used as a factor in the reduction of stress.

Additionally, there are no stock for response action, biological stability, or cognitive stability in this version of the diagram (although they may be added in future). Other factors are shown as parameters (represented as oval shapes). Inflow and outflow calculations are shown moving from sources through the stock (rectangles) and out into sink states (both source/sink are represented as clouds). Below are brief descriptions of the stocks and flows of figure 5:

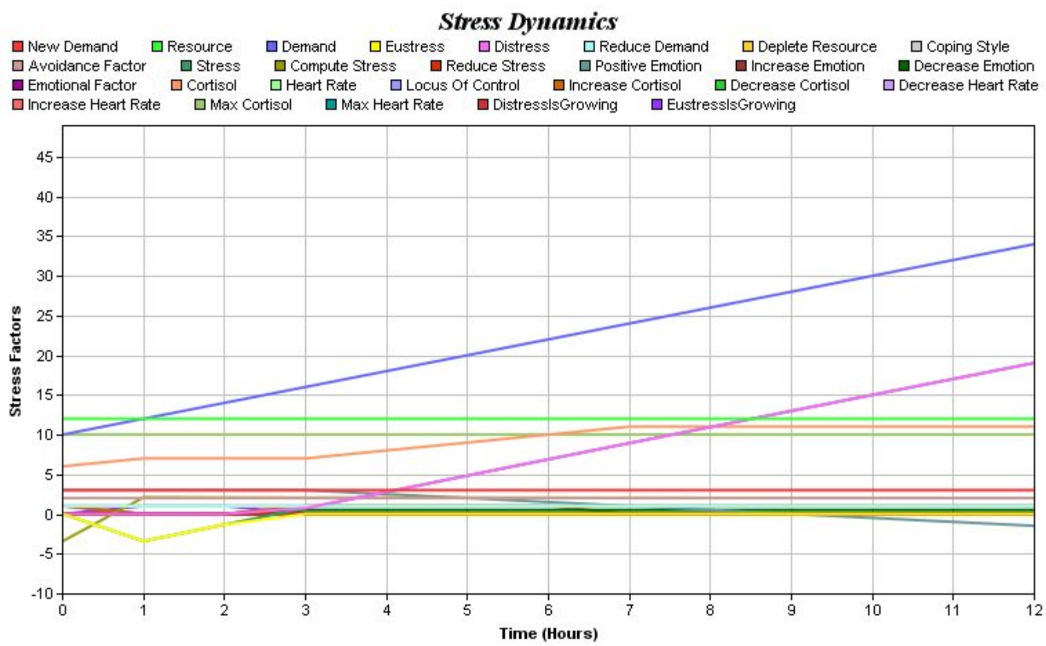

Fig. 6. A sample of possible results from stock and flow modelling.

Demand In this system Demand begins at an initial level of 10 units that must be serviced. It is influenced by an inflow of New Demand at a rate of two units per hour (in our test cases). It is reduced by a rate of 1 unit per hour whenever there is Eustress or Distress. This computation of reducing demand must factor in the coping style being performed, since its flows, along with those of the Resource stock, are combined to represent the response action.

Resource Resources in the system begin with a value of 12 units. The rate of increase for a new resource is set arbitrarily at one unit per hour. The depletion

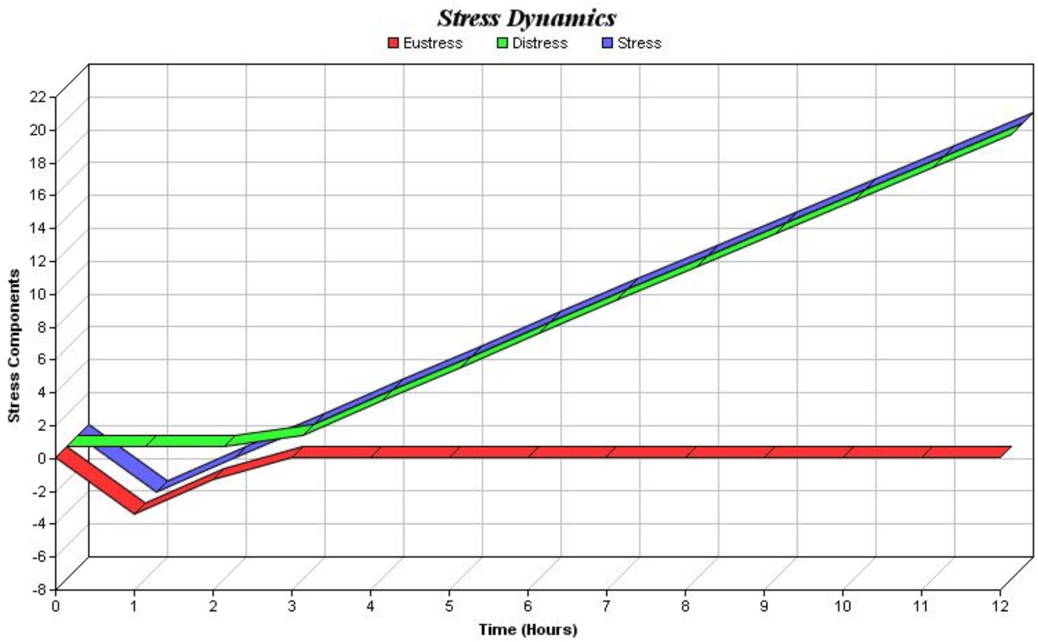

Fig. 7. A sample view of stress levels of eustress, distress, and stress.

of resources is computed as a function of Distress, Eustress, Demand, and the Coping style selected. For both action-oriented, and emotion-oriented coping a response action is represented by a depletion of a resource that affects demand as long as there is either Eustress or Distress present. Avoidant coping has no effect on demand or resources in this version of the model. Future versions may likely incorporate avoidant coping.

Stress Stress is set initially at 0 units, and grows according to the Compute Stress inflow of figure 5. Stress is computed as a function of Demand, Resource, Emotion, and Locus of Control. Stress is reduced according to coping style, and the computation of demand minus the ratio of demand to positive emotion, resources and previous stress level multiplied by the ratio of locus of control. Locus of control is a parameter that is either positive or negative, representing internal, and external locus of control, respectively.

Additionally, Stress is subdivided into two groups, distress, and eustress, according to the ratio of resources to demands. If demands are greater than resources then the value of stress will be positive, representing distress; if demand is less than resources stress will then be negative, corresponding to the state of distress. If the computation is zero then it is assumed that both distress and eustress are zero.

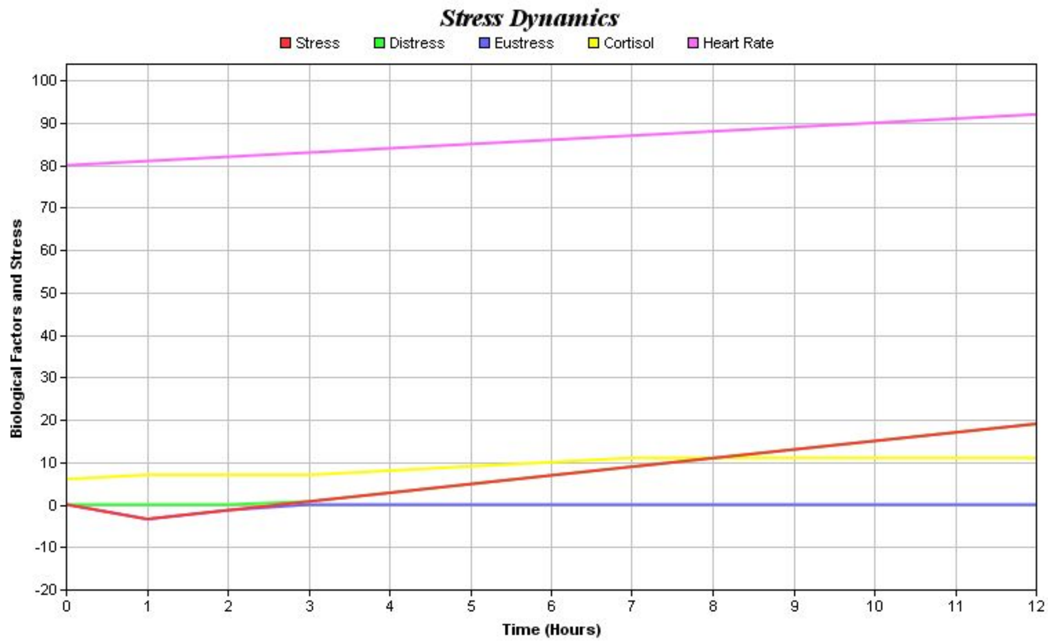

Fig. 8. A sample view of biological factors and stress levels.

Positive Emotion Emotion is set initially at three emotional units, and is increased by inflows of an emotional factor, as seen in figure 5. Emotions are shown as decreasing by one unit per hour whenever there is distress.

Cortisol As one of the two biological factors in this model, cortisol is a stock with an initial value of 6 units, an average value according to studies in [10]. The level of cortisol increases by a rate of one unit per hour, whenever distress is growing, until a max rate of 10 units is reached. It decreases by the same rate whenever distress is not growing.

Heart Rate Heart rate is shown in the model as a stock with an initial value of 80 units, the average/baseline, according to [10]. This value increases until a max rate of 110 until whenever distress or eustress are growing. When these are not growing the value decreases by one unit per hour.

Notes This design remains a work in progress and is subject to change.

4 Behavioral Output of a Stress Dynamic Model

Using the stocks and flows diagram above, it is possible to simulate the behavior of stress in a quantifiable manner. The figures mentioned below are indicative of what can be derived from these systems using the SimGua tool, [20], based on the design decisions described previously. They represent a proof of concept to show that the use of system dynamics for fuzzy human factor modelling is viable. For example, in figure 6 one can see that as demand exceeds resources at timestep 3, it causes the level of stress to change from eustress to distress after some delay, at timestep 5. Also, it is possible to isolate certain key variables such as the components of stress, as in figure 7, or the biological factors and resulting stress over time, as in figure 8.

5 Discussion

The models above are a preliminary step to studies involving human-factor modules for use in computer programs. It has been derived from earlier definitions in psychology, and assembled into system dynamics causal loop diagrams and a resulting stock and flows diagram. Other similar modelling approaches in the literature remain, and need to be assessed against this current approach. Several main questions remain, namely about how we can extend and translate this model (and approach) so it may be useful for quantifying other interesting human factors. In a longer term perspective it will be interesting to explore how these different human factors interrelate in order to better understand the complexities of human behavior for different applications.

It is important to validate any such model of human factors rigorously to ensure that the models have explanatory value that approximates behavior. In order to do this they should be reviewed by domain experts, most likely using causal loop diagrams to facilitate discussion since they are easily understood in relation to more subjective, fuzzy definitions. This paper has explored the general question of how to quantify such fuzzy notions in a way that may be computable for future studies and implementations, such as agent based simulations of organizational policies and work practices.

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