UNIVERSITY OF AGDER

Managing Disorganization in a Disaster Case

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This Masters Thesis is carried out as a part of the education at the University of Agder and is therefore approved as a part of this education. However, this does not imply that the University answers for the methods that are used or the conclusions that are drawn.

University of Agder, May 2012
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Abstract

This thesis has five main goals. The first goal is to attempt to replicate the system dynamics model "The essence of transformation in a selforganizing team" by Tu et al, with the modelling tool Vensim. "The essence of transformation in a selforganizing team" deals with managing disorganizing using imperical data from the Palau Case.

The other four goals include a review of Tu et al.'s model, implementing proposals for improvement, expressing the implications for the model for better crisis management, and if real data can be found describe a different case of emergency management.

We approached this problem by reviewing and testing Tu et al.'s iThink model, and replicated it into a Vensim model. The equations were tested and applied the correct unit and polarity. The model was also simplified by removing unnecessary equations and the model was applied to a new crisis case (Hatlestad case).

Our results show that our simplified model can be used in disaster planning, with only minor changes to the variables other disaster cases where the situation goes from chaos to control can be modelled.

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Acknowledgements

This thesis is a document for the master thesis course IKT 590 from the master programme at Faculty of Engineering and Science at University of Agder, Grimstad. This thesis, *"Managing Disorganization in a Disaster Case"* was initially proposed and supervised by Jose J. Gonzalez, Professor at University of Agder.

We would like to thank Professor Gonzalez for good guidance through the entire project. He has used a lot of time and effort to guide us on our way in this thesis.

We would like to thank Magne Myrtveit from Dynaplan for supporting us with a free version of Dynaplan SMIA that we used in the beginning of the analyzing phase.

We would also like to thank Ya-tsai Tseng with feedback on questions related to their model and work. Without their help and the iThink model our project would not have been possible.

Grimstad, June 1, 2012

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Chapter 1

Introduction

1.1 Motivation

In the recent years there has been a growing recognition that plans for disaster management all too often fail in practice [1][2]. Disasters do not follow scripts and the unexpected always happens are catching phrases to this effect (Sox First, 2011).

Tu et al. [3] have recently developed a system dynamics model that describes the transition from a crisis management team in a state of disorganization and information overload to a self organized team that handles the emergency efficiently. The emergency case relates to navigating a vessel in critical conditions of breakdown of the navigation system.

This is a very interesting case, as it is the first time that anyone has developed a system dynamics model for managing disorganization. In the best tradition of science, it is important for an independent team to attempt to reproduce the model and it's results.

1.2 Thesis Problem and Goals

The main objective of this thesis is to make a simple general model of self organization based on Tu et al.'s (iThink) [3] model. This new model should be usable in crisis management planning.

The goals of this project include:

1. Implementing a new version of the system dynamics model by Tu et al. [3] using the modelling tool Vensim.

2. Critical review of Tu et al.'s model with proposals for improvement.

3. Implementing proposals for improvement: a simpler, clearer, better documented model with variable units and less number of table variables.

4. Expressing the implications of the model for better crisis management.

5. If real data can be found, use the model to describe a different case of emergency management.

1.3 Limitations and Key Assumptions

When it comes to anaylzing Hatlestad case, we make some assumptions about some variables that are hard to get accurate data. We base our data on the case on Lango's book [4] and rely on the data as being accurate. In some cases where Lango has used estimates, we have used the same estimates.

1.4 Target Audience

This thesis is intended to be read by researchers, scientists and students interested in System Dynamics, and specially System Dynamic models that embrace the managing of disorganization in disaster situations, catastrophic events or emergency situations. It is written at a technical level where fellow students or people with similar background in ICT should be able to grasp the content.

1.5 Thesis Outline

The thesis is divided into five main parts: *Introduction, Background, Critical Review of the Model, Case* and *Conclusion*

The *Introduction* introduces the Self organizing model by Tu et al. [3] together with the thesis problems and goals. It also describes the limitations and key assumptions for this thesis.

The *Background* gives an introduction to the Palau case which Tu et al.'s model is based and implemented on.

The *Critical Review of the Model* chapter gives a review of Tu et al.'s model, with proposals for improvements.

Conversion and Simplification of the Model explains how the Tu et al.'s model

is converted to the modeling tool Vensim, and the process behind this work. The chapter also contains valiation test to enhance the confidence in the model.

The *Case* chapter describes the implementation on the Hatlestad case based on Vensim3 (Table 1.1).

The last chapter *Conclusion* summaries our findings and gives a conclusion.

1.6   Model Names

Table 1.1: Model Names

Model Name	File Name	Description	Appendix
iThink1a	iThink1a.itm	Model received by Tu et al. on Palau case	Appendix A (Without the orange loop)
iThink1b	iThink1b.itm	Same as iThink1a, but with CCRAT changed from 5 to 4 in order to get the correct graph behaviour, same behavior as the graphs in the published paper by Tu et al.	Appendix A (Without the orange loop)
iThink2	iThink2.itm	iThink1b with fixed loop from *Error Detection Skill* to *Effect of Cognition for ED&R on Errors*	Appendix A
Vensim1	Vensim1.mdl	Conversion of iThink2 to Vensim, with units and polarity added	Appendix B.1
Vensim2	Vensim2.mdl	Simplification of Vensim1, by stipping the model down	Appendix C
Vensim3	Vensim3.mdl	Rebuilt model of Vensim1 based on the knowledge gained when simplifying (Vensim2)	Appendix D.1
Hatlestad1	Hatlestad1.mdl	Vensim3 on Hatlestad case with *ManPower* as a stock and flow	Appendix D.1

Chapter 2

Background

2.1 The Essence of Transformation in a Self-organizing Team Explained

2.1.1 Navigation Case

The Paper "The essence of transformation in a self organizing team" by Tu et al. [3] is based on data from Hutchins book *Cognition in the Wild* [4]. Hutchins data collection was performed on the ship "Palau", on a four-day journey. On the last entry to the port the ship lost its power, and all electrical systems shut down. The navigation crew had to guide the ship into port despite the malfunctioning equipment. This was a highly demanding situation, where a number of situations could have resulted in catastrophic consequences for the ships crew. The navigation was performed based on an activity cycle, where the distance to known landmark were calculated manualy. After some period of time the same calculations were performed guiding the ship forward. When the ship came closer to the port the cycle interval was decreased. The critical part of the navigation team consisted of a plotter(one person), bearing time recorder(one person) and bearing

takers(two persons).

Hutchinsen divided the navigation case into 4 different stages:

Stage 1 (10th to 35th minute) describes the ship's approach to the port, where *Actual Work Rate*(amount of tasks a crew member has to perform each minute) increases towards *Desired Work rate*(amount of tasks in total that has to be performed in order to navigate the ship safely). As a consequence, *Cognitive Load*(mental process related to handeling stress and performing under pressure) increased due to the increase of *Actual work rate*. In this stage *Local Innovations and Changes*(a way to do a task more efficiently, for instace with the use of tools) are not active, and does not dominate the behaviour. This is mainly because the plotter is doing all the computation him self, while the rest of the crew is waiting.

Stage 2 (36th to 45th minute) shows the *Actual Work Rate* declines because of the increased rate of errors. This effect is again caused due to increased *Cognitive Load Pressure*. In this stage the crew starts to do *Local Innovations and Changes* by using tools and new more efficient ways of completing tasks.

The *Local Innovations and Changes* has a side effect making confusion between crew members leading to a negative effect on *Mutual Understanding*, which effects of increasing *Errors from Mismatch* (Errors made from dooing a task incorrect), which in the end reduces *Actual Work rate*.

Stage 3 (46th to 160th minute) describes how the *Actual Work Rate* goes from dropping to increasing. *Cognitive Load* is still high and *Local Innovations and Changes* are still running high. *Mutual Understanding* drops a bit, before increasing, while *Errors from Mismatch* decreases. *Average Error Rate* is reduced while the crew detects errors, leaving the total Error unchanged.

Stage 4 (160th to 250th minute) In this stage *Mutual Understanding* is increased and *Errors from Mismatch* is decreased to almost zero. *Local Innovations and Changes* no longer exists, and *Actual Work Rate* is equal to *Desired Work Rate*.

Chapter 3

Critical Review of the Model

Tu et al. have developed a system dynamics model that is ground-breaking in system dynamics context. The model is one of the first models on "managing disorganization". The model shows different aspects of managing disorganization with variables such as *Mutual understanding* and *Cognitive Load*, and how *Work Rate* is affected by these variables.

3.1 Loops

In the analysis phase we started to locate the major loops in the model, and here we found a loop described in the paper, which was not in the iThink1a (Table 1.1) model. We contacted Ya-tsai(one of the authors in Tu et al) and asked for help concerning the missing loop. She replied that the iThink1a model was a test version and sent us the correct model (iThink2 Table 1.1). The loop that was missing was the connection from *Error Detection Skill* to *Effect of Cognition for ED&R on Errors* (see Appendix A). After correcting this problem, we compared the iThink2 model with the graphs from the paper and they were not identical. This indicates that the iThink2 is not the one used in the published paper by Tu et al. After some

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correspondance with Ya-tsai, she informed us that they had by mistake, published
the wrong graphs in the paper. Even though the graphs were not identical, they do
have same behaviour. Figure 3.1, 3.2, 3.3 and 3.4 shows the difference between
the published graphs (iThink1b) and Vensim1. The main conclusions from Tu et
al.'s paper are still correct, even with the corrected graphs.
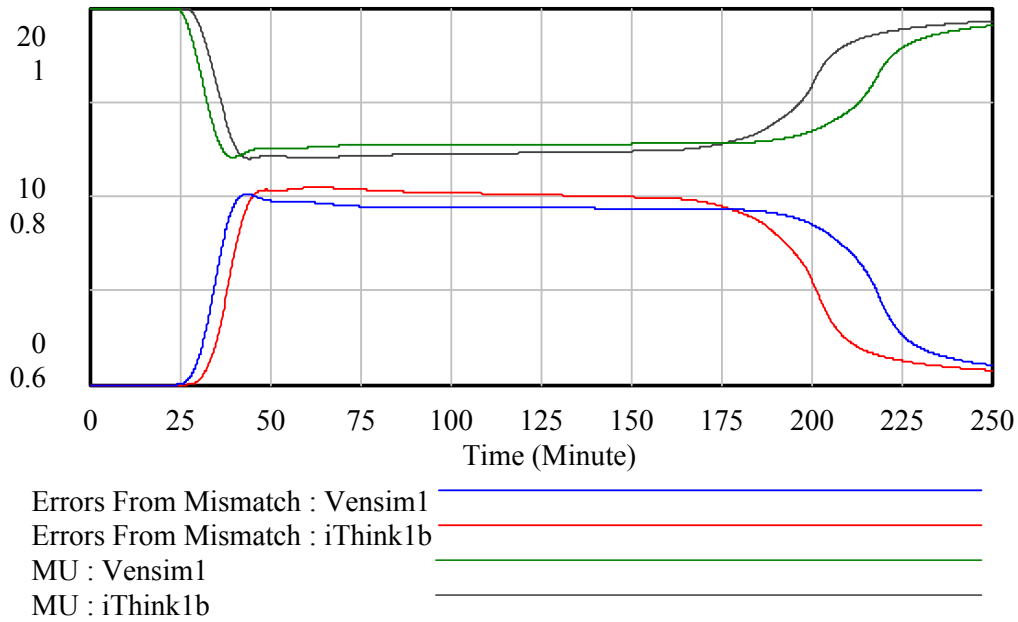
Figure 3.1: Comparison 1 of the Published and Vensim1 model

Average Error Rate : Vensim1
Average Error Rate : iThink1b
Errors : Vensim1
Errors : iThink1b
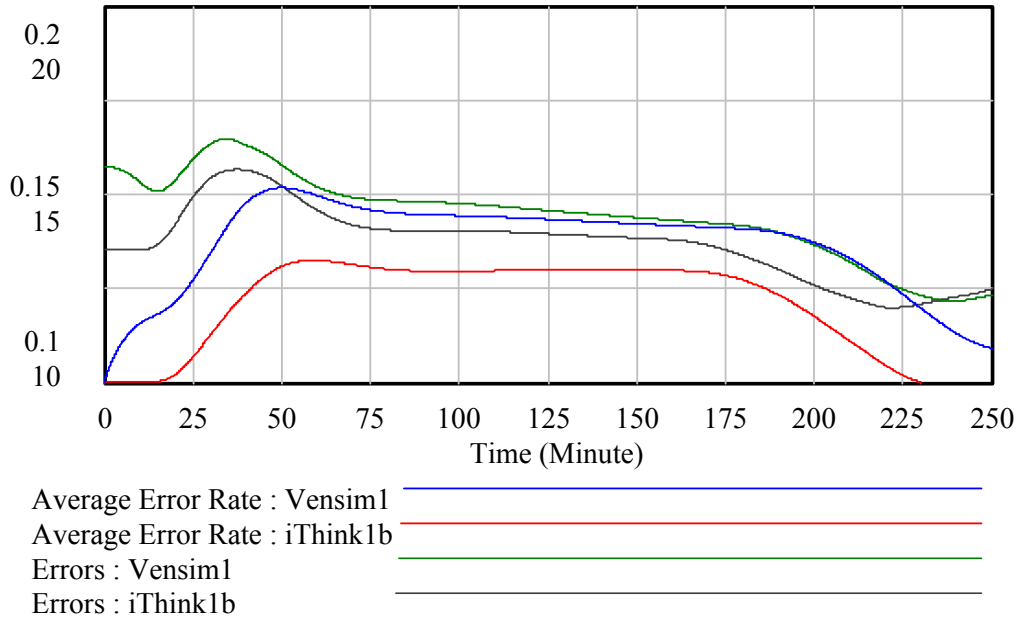
Figure 3.2: Comparison 2 of the Published and Vensim1 model

Desired Work Rate : Vensim1
Desired Work Rate : iThink1b
Actual Work Rate : Vensim1
Actual Work Rate : iThink1b
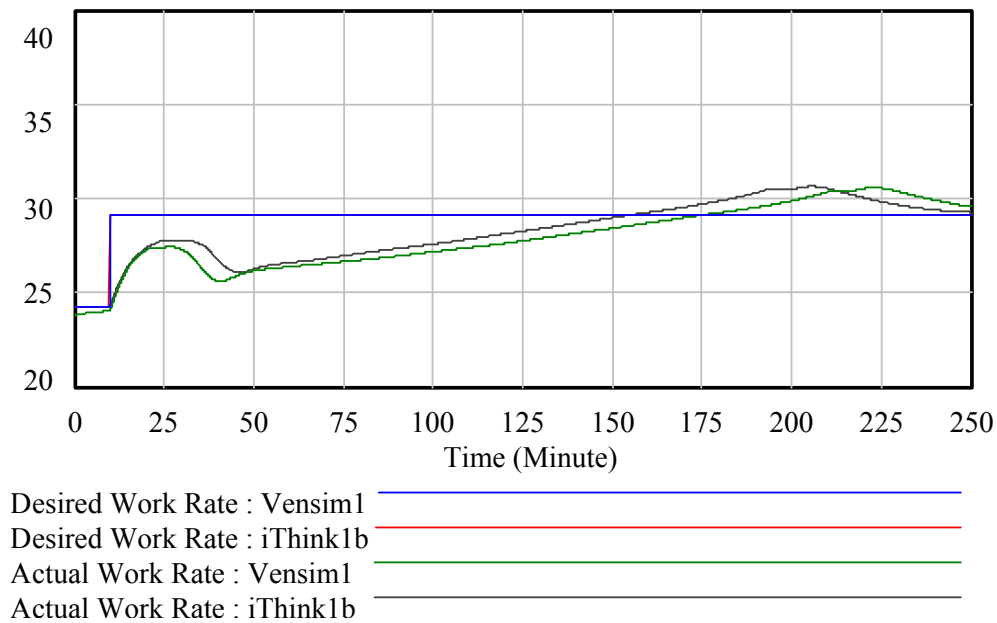
Figure 3.3: Comparison 3 of the Published and Vensim1 model

Cognitive Load : Vensim1
Cognitive Load : iThink1b
Local Innovations and Changes : Vensim1
Local Innovations and Changes : iThink1b
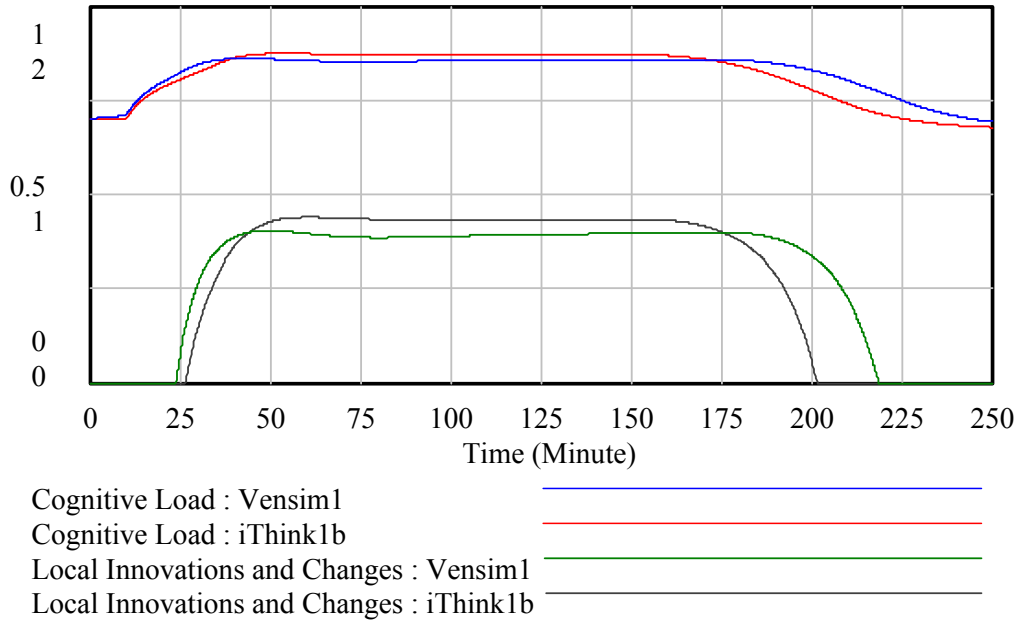
Figure 3.4: Comparison 4 of the Published and Vensim1 model

3.2 Polarity

Tu et al.'s model does not contain any polarity (+ and -). With correct polarity it is possible to understand how inner loops of the model behave, and what variables that controls the main behaviour. This is not a requirement, but makes the model easier to understand, and explain to people with minor experience with understanding system dynamics models.

3.3 Units

Tu et al.'s iThink model was generic and did not include the ability to use real measurable units (meters, seconds, numbers of persons, number of task, etc). When trying to understand the model and the model equations we had to guess what units the model equations should be based on. A model with units make it easier to understand for a larger amount of people. Correct units in the design phase will make the model better structured and having less probability of having defects.

3.4 Reservoir

In Tu et al.s iThink2 (Table 1.1) model they used a "Reservoir" which is a sub system for *Mutual Understanding*. Vensim don't have this sub system. After correspondence with Ya-tsai, it was found out that the "Reservoir" could be treated as a normal "Stock and Flow" in Vensim. It was concluded that the use of "Reservoir" only adds complexity to the model and do not contribute and could be removed from the model.

3.5 Model Testing

Model testing/validating is an important step in system dynamics methodology. There is no given test that can validate any model, but there are tests that can enhance the confidence of a given model [5, p.209]. The normal way to gain confidence is to "validate" the model. Coyle [6, p.362] has outlined three main test that can be used to validate a system dynamics model. These tests include:

- Verification test that are concerned with verifying that the structure and parameters of the real system has been correctly converted into the model.

- Validation test that are concerned with demonstrating that the model generate the same type of behaviour as we will expect from the real case.

- Legitimation test that are concerned with determining that the model follows the laws of system structure and accepted rules.

We have performed the following tests to gain confidence in the iThink2 (Table 1.1) model.

- The causal loop diagram must correspond to the statement of the problem

- The equations must correspond to the causal loop diagram;in particular the + and the - signs in the equations must match the signs in the causal loop model section.

- The model must be dimensionally valid (Has each equation in the model been checked for dimensional consistency

- Has each equation in the model been adequately documented?

- The model does not produce any unrealistic values?

The causal loop diagram must correspond to the statement of the problem

In the Palau-case there are four main causal loop diagram; "Local innovation", "Performance adjustment", "Self referencing" and "Error detection and recovery". In the navigation case, the team members with their respectable tasks attempts to relieve task pressure by doing "Local Innovation". "Local Innovation" are tasks such as using a calculator, notes, ruler and asking other team members for help. "Local Innovation" behaviour also affect the *Cognitive Load Pressure* by reducing the *Mutual Understanding* amongst team members. This negative side effect is caused by team members that tries to increase efficiency.
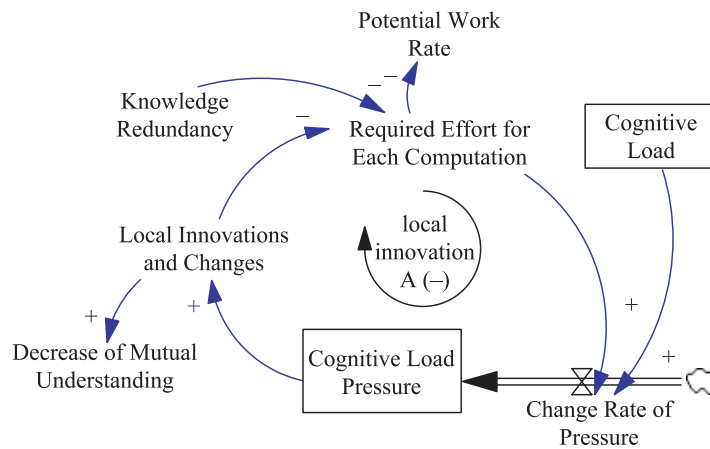
Figure 3.5: Local Innovation Loop [3, p.143]

Performance adjustment

In Figure 3.6 Performance adjustment loop shows how performance adjustment was managed. When the Performance Gap which is the difference between *Desired Work Rate* and *Actual Work Rate*, is positive, the *Cognitive Load* is increased by adjusting the *Cognition Resource Allocation*. This action lead to more *Potential Work Rate*, which increases *Actual Work Rate*.

Desired Work Rate denotes the amount of tasks needed to be completed to be able to navigate the ship. The variable *Actual Work Rate* tells the number of activities completed per minute by the navigation team.
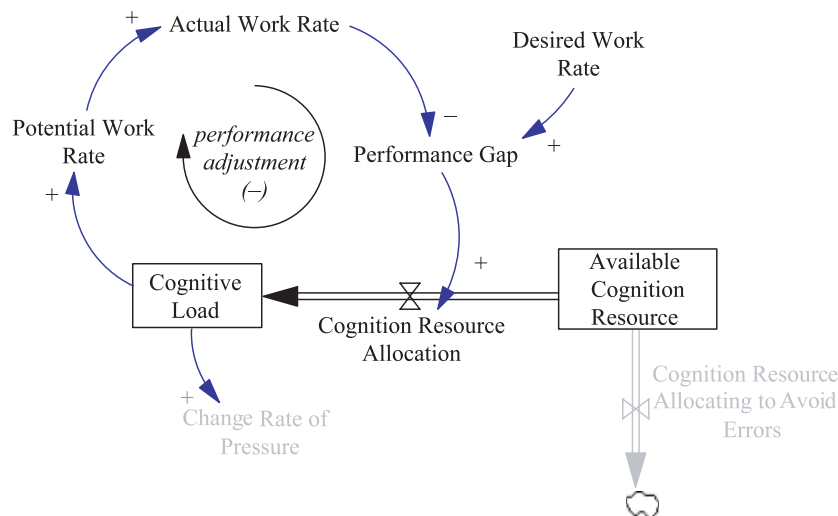
Figure 3.6: Performance Adjustment Loop [3, p.142]

Self referencing

To be able to work together in a team good communication is essential which also means that each team member has to have a mutual understanding of what and how they are suppose to perform at any given task. Higher *Mutual Understanding* leads to better communication amongst team members, which to some extent is build on *Knowledge Redundancy*. *Knowledge Redundancy* refers to con-

cept that team members have shared knowledge about how a tasks should be performed. *Knowledge Redundancy* can be achieved by having job rotations. While increased *Mutual Understanding* leads to better communication the drawback affects decrease of structure in the team which decreases *Mutual Understanding*.
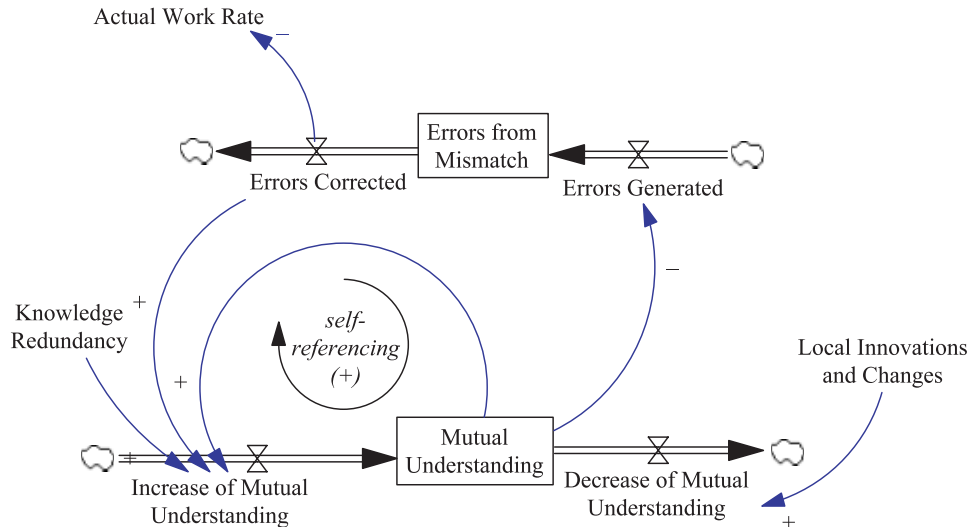
Figure 3.7: Self Referencing Loop [3, p.144]

Error detection and recovery

Figure 3.8 shows that errors occurred from the team members due to high *Cognitive Load Pressure*. [4, p.272], describes three types of actions to deal with such errors: preventing errors, facilitating system recovery and learning from mistakes.
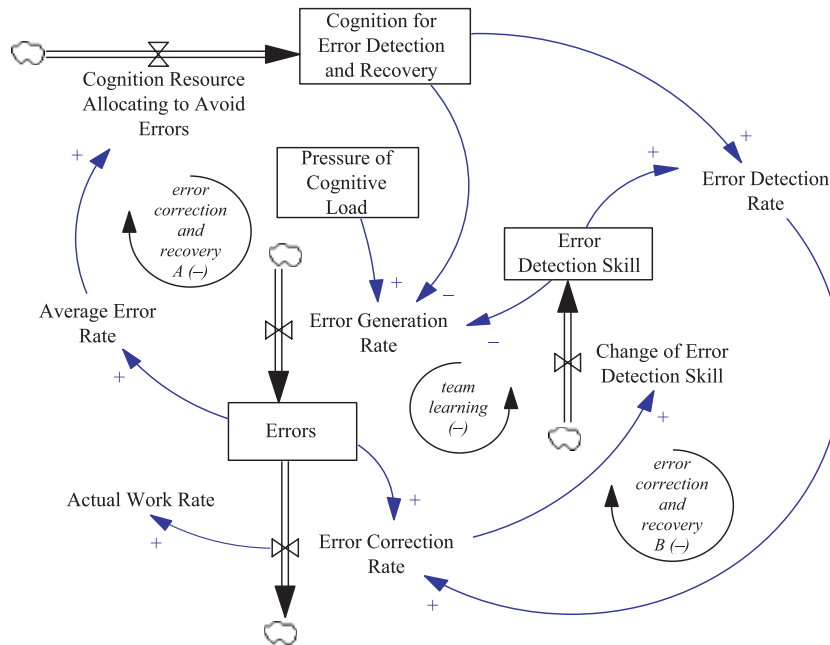
Figure 3.8: Error Detection and Recovery Loop [3, p.145]

The equations must correspond to the causal loop diagram;in particular the "+" and the "-" signs in the equations must match the signs in the causal loop model section.

A close inspection comparing the "+" and "-" in the model equations shows that they match the causal loop diagrams "+" and "-".

The model must be dimensionally valid (Has each equation in the model been checked for dimensional consistency?)

The model did not contain any units for the equations. This had to be added manually, and the model had to be altered (added more variables) to gain the dimensional consistency.

Has each equation in the model been adequately documented?

Since most of the model equations is based on Tu et al.'s equations which lack the proper documentation, it is difficult to provide adequately documentation.

The model does not produce any unrealistic values.

To find out if the model does produce any unrealistic value we perform a sensitivity analysis. In this analysis we increase all the variable's value with 10% and decrease the same values with 10%. The results will show if there are any unrealistic values between this limits. Table 3.1 shows the values of the variables used in the sensitivity analysis.

Table 3.1: Sensitivity Experiments for Testing Parameters in the Palau-case

Variable	Base case values	10% increase	10% decrease
CAT	10	11	9
COEAT	10	11	9
CCRAT	5	5.5	4.5
PSAT	10	11	9
CLSAT	5	5.5	4.5
MUDAT	3	3.3	2.7
Shared Mu Adjustment	0.2	0.22	0.18
Normal EGR	0.1	0.11	0.09
EDS Normal Increase Rate	0.002	0.0022	0.0018
Increased EDS per CE	1	1.1	0.9
AERAT	5	5.5	4.5
Total ManPower	8	8.8	7.2
Senior Junior Team Members	0.5	0.55	0.45

The graph in Figure 3.9 shows that the *Actual Work Rate* with 10% increase,10% decrease and base score gives slightly different outcome. The different outcome is mainly affected of the number of people in the three tests with "7,2" in the 10% decrease and 8.8 in the 10% increased case.

The *Cognitive Load and Local Innovations and Changes* shows the same behaviour with only minor change at the end. Here we conclude that this is because of variables that are less sensitive and therefore make a smaller change to the output.
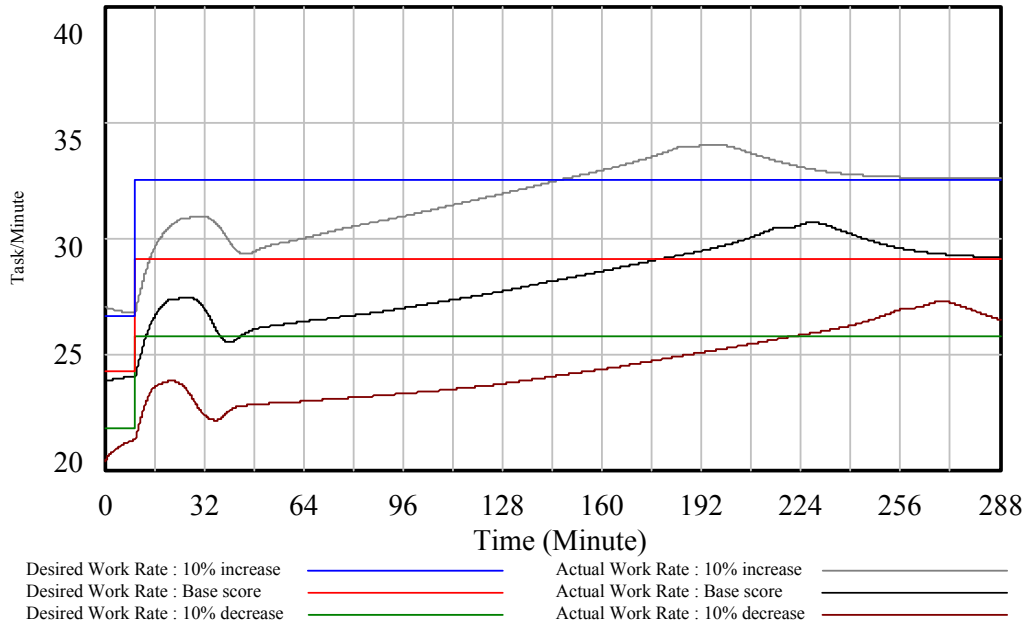
Figure 3.9: Sensitivity Graph Vensim1 Model
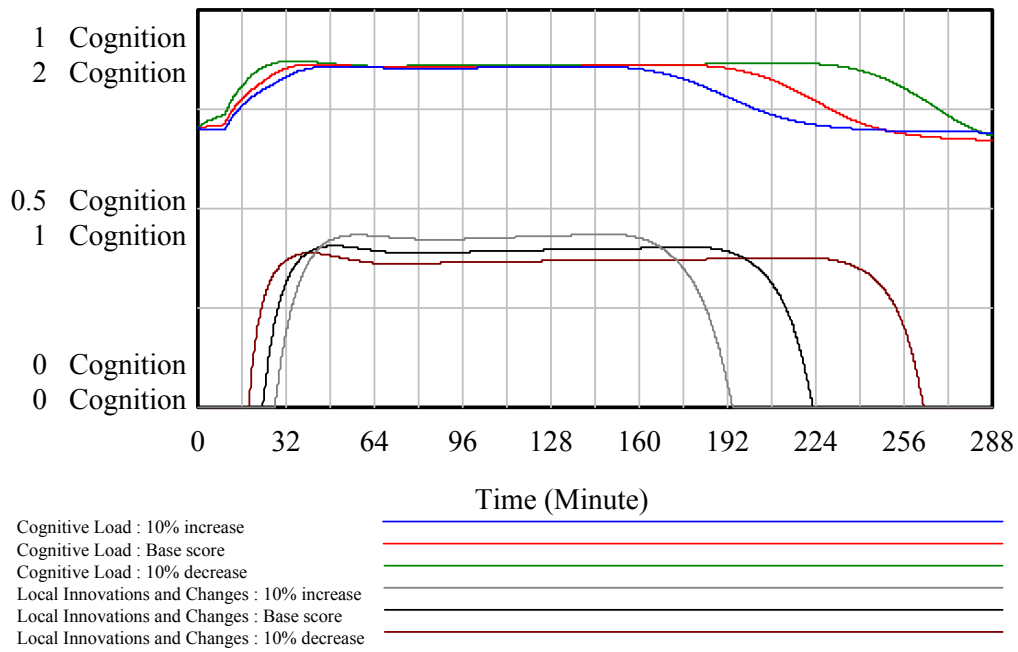
Figure 3.10: Sensitivity Graph Vensim1 Model

In the graph 3.11 we see the same behaviour on *Errors from Mismatch* and *Mutual Understanding* for the three tests (10% increase, base score and 10% decrease). They all have the same behaviour with a slightly different shift.
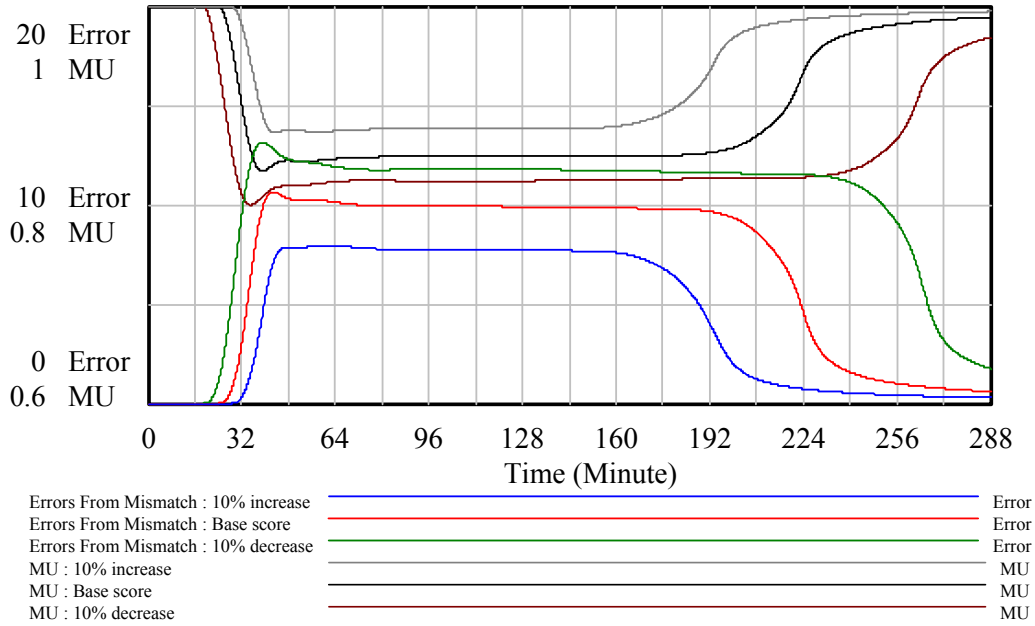
Figure 3.11: Sensitivity Graph Vensim1 Model
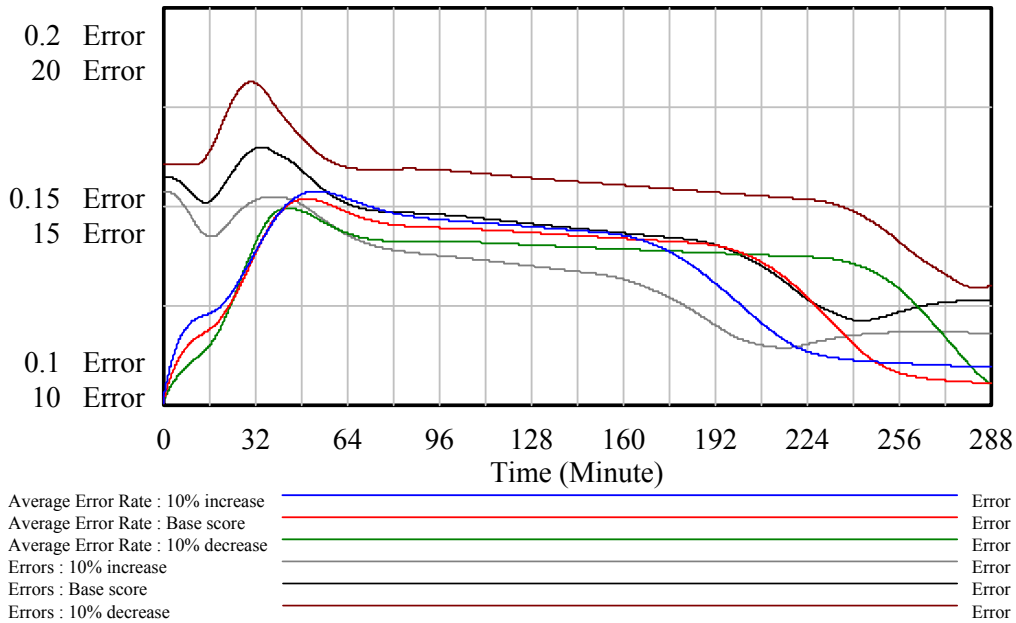
Figure 3.12: Sensitivity Graph Vensim1 Model

Table 3.2: Sensitivity Analysis

Variable	Not Sensitive	Sensitive	Very Sensitive	Highly Sensitive
CAT	*			
COEAT		*		
CCRAT		*		
PSAT	*			
CLSAT	*			
MUDAT		*		
Shared MU Adjustment		*		
Normal EGR		*		
EDS Normal Increase Rate	*			
Increased EDS per CE	*			
AERAT	*			
Total ManPower				*
Senior Junior Team Members				*

Table 3.2 shows how sensitive each of the varibles are when varying each variable one at a time between +10% and -10% from the base score. The variables are ranked based on their sensitivity. The sensitivity is ranged in following groups; "Not Sensitive (below 5%)", "Sensitive (5-14%)", Very Sensitive (15-34%)", and Highly Sensitive (above 35%).

Chapter 4

Conversion and Simplification of the Model

4.1 Conversion of the Model from iThink to Vensim

The Vensim1 (Table 1.1) used the original equations and structure from the iThink2 (Table 1.1). There are some differences on how models are built in Vensim and iThink, and therefore the two models do not look the same. For instance iThink is using sector frames to separate the model into modules while Vensim uses views. The main difference between sector frames and views are that sector frames are all on one page and all the modules can be viewed at the same time. In *Vensim views* you have to switch between different views so you can't see all the models modules at the same time (the Vensim views are connected to each other with the use of shadow variables). Another major difference is that a sub-model is used in iThink *Cognitive Load* module. This module is not necessary and just add more complexity to the model. The Cognitive Load module was put directly in the Vensim model. The Vensim model in the Tu at al.'s paper had polarity added to the arrows which made it easier to interpret how the different variables affected each

other, but this was not applied in the larger iThink model. In order to make it easier to grasp how the different variables affect each other, polarity were added to the *Vensim* model. Some of the arrows were overlapping each other which are ok, but if it is possible to avoid it the model will be clearer and easier to read. Understandably this was not the main focus in the iThink model since it was not published in the Tu et al. paper, but was only used for the results/graphs. In the Vensim1 model unnecessary crossing of arrows were fixed. After the model was completed the iThink2 equation list was applied to the Vensim1 model. There are some minor syntax differences between Vensim and iThink so the equations had to be applied manually and some equations became different after replacing the sub-model.

To verify the results in the iThink1b model from Tu et al.'s paper the same results in the Vensim model must occur. They include; *Desired Work Rate*, *Actual Work Rate*, *Cognitive Load*, *Local Innovations and Changes*, *Mutual Understanding*, *Errors from Mismatch*, *Average Error Rate* and *Errors*. First a control comparison was conducted on the graphs from Tu et al.'s paper and the graphs in the iThink1b model to be 100% certain that it gave the correct data. The results were the same which verified what was already expected.

4.1.1 Implementation of The Proposed Improvements

Adding Units

The iThink model from Tu et al. did not have units implemented. Units had to be added not only to make it easier to understand the model, but to verify that all the variables were consistent as well. In order to set the correct units every single variable had to be analyzed, the unit was then determined by looking at the equation and the unit of the variable input of the equation.

The first step was to predict the expected units at the *stock and flow* variables. This was done by looking at the name of the variables. It was not always clear what type of unit that should be used, but the selection was performed by the author's best effort. In the next step the variables of the type *constant* were added their units, and from that point on the variables with the *constants* as input were added their units and so on and so forth.

After adding all the units, some of the variable units were inconsistent. To solve this extra variables had to be added in order to get the consistent units. The added variables did not affect the behaviour of the model in any way. In total 5 new variables had to be added; *Effect of EDR on ECR*, *Effect of PWR on Error Rates*, *Effect of Average Error Rate on AEAR*, *Effect of PWR and MU on EG* and *Effect of ECR and EC on AWR*, for more details see Appendix B.1.

Here is an example that explains one of the unit inconsistencies and how it was corrected, see Figure 4.1 and 4.2 for comparison before and after.
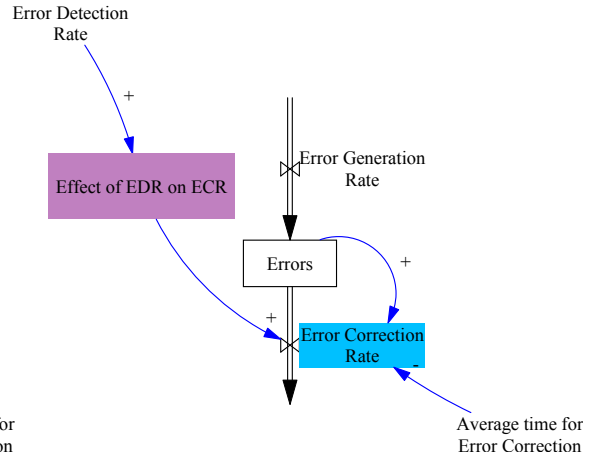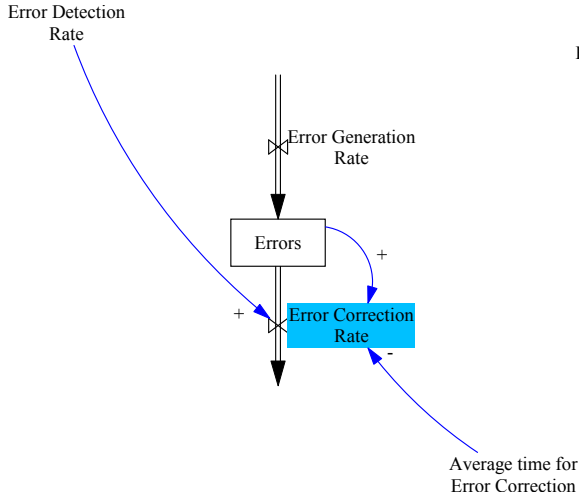
Figure 4.1: Example of *Error Correction Rate* as it was in iThink2

Figure 4.2: Example of *Error Correction Rate* With Unit Correction

Error Correction Rate (marked as blue) should have the rate $\dfrac{Error}{Minute}$, at Figure 4.1 the equation of *Error Correction Rate* looks like this

$$\frac{Error\,Detection\,Rate * Errors}{Average\,time\,for\,Error\,Correction}$$

which units are

$$\frac{\dfrac{Error}{Minute} * Error}{Minute} = \frac{Error^2}{Minute^2}.$$

In order to solve this we added a variable *Effect of EDR on ECR* (marked as pink in Figure 4.2). *Effect of EDR on ECRs* unit is defined as dimensionless and is the effect of *Error Detection Rate* on *Error Correction Rate*. The equation of *Error Correction Rates* was changed to

$$\frac{Effect\,of\,EDR\,on\,ECR * Errors}{Average\,time\,for\,Error\,Correction}$$

which in units are

$$\frac{Dmnl * Error}{Minute} = \frac{Error}{Minute}.$$

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Adding Polarities

The link between two variables is made by an arrow going from one variable to another, and is a casual relationship.

The link can influence the variable in one of two ways [7][1]:

1. The variable can be affected in the same direction also called positive polarity represented by a (+) sign or a (S).

2. The other possibility is that the variable can be affected in the opposite direction also called negative polarity represented by a (-) or an (O).

In order to set the correct polarity all the equation had to be analyzed for every variable. The Figure 4.3 below shows a simple example of a casual relationship from Vensim1(Table 1.1) with the equation:

$$Effect\ of\ Senior\ Junior\ Percentage\ on\ Work\ Rate *$$
$$Normal\ Ammount\ of\ Computing\ Tasks * (1 - Communication\ Overhead)$$
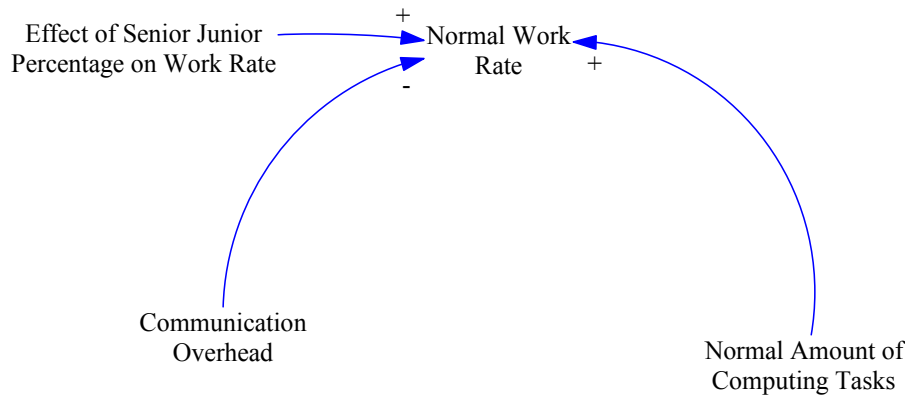
Figure 4.3: Polarity Example

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[1]In this paper (+) and (-) notations are used to describe the polarity.

If *Effect of Senior Junior Precentage on Work Rate* increas the *Normal Work Rate* increas, if *Effect of Senior Junior Precentage on Work Rate* decrease the *Normal Work Rate* decrease. Therefore positive (+) polarity.

If *Normal Amount of Computing Tasks* increas the *Normal Work Rate* increas, if *Normal Amount of Computing Tasks* decrease the *Normal Work Rate* decrease. Therefore positive (+) polarity.

If *Communication Overhead* increas the *Normal Work Rate* decrease, if *Normal Amount of Computing Tasks* decrease the *Normal Work Rate* increase. Therefore negative (-) polarity.

4.2   Why Simplify the Model?

The iThink model by Tu et al. is very large and complex. Such a complex model is very difficult to understand and implement in real life. We therefore feel it is required to simplify and reduce complexity to increase the model usability. In the paper *"How small system dynamics models can help the public police process"* [8] by Ghaffarzadegan et al. they examine why small system dynamic models are useful in policy making. According to Ghaffarzadegan et al.'s research on small model size:

Quotes from Ghaffarzadegan et al.'s paper [8, p.37]:

"Small size allows for exhaustive experimentation and sensitivity analysis, wise interpretation of parameters and parameter changes"

"Small size ensures that the results of experiments can be fully and easily understood by policymakers"

"Small size facilitates presentation of lessons to others. Short exposition and holistic view made possible"

"Small size ensures that model insights are fully understood, allowing policy-

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makers to appreciate and address their own overconfidence"

"Small size allows individuals to see the feedback structure as a whole and not be frustrated by the need to track many variables and links at once"

To make the model smaller, aggregation or merging is suggested to get less variables. Though aggregation is a great way to make a model smaller, it is important to know that models that are aggregated may lose detailed information. [8, p.40]. In our remodelling we have tested for this effect and avoided aggregation of variables that made a difference to the final result.

4.3 The Simplification

The Vensim1 model (Table 1.1) was simplified using two different approaches in order to get the best results. Vensim2 model (Table 1.1) was simplified by using the Vensim1 and stripping it down and removing unnecessary variables, merging variables and replacing tables with equations (this was performed where the tables made a straight line or close to a straight line).

The second method was to rebuilding the Vensim1 by starting with the main stocks and flows, and then adding variables in a step-by-step manner. When we did this we used our knowledge from the first simplification to get as few variables as possible and still maintain accuracy.

This method was much more difficult than the first method since we could not always see the results (the graphs) during the building process. This could for instance be due to overflows during simulations. Even though it is easier to make the model smaller with this method compared to the first method, it is far more difficult to get the same behaviour. Some more details on the simplification process are listed below.

4.3.1 Stripping The Vensim1 Model

The model was simplified by using a systematic approach where all the variables were analyzed to see how the variables affected each other. All the variables that were removed can be seen in Table 4.1. Table 4.2 explains why the variables were removed. In most cases it were either merged with another variable or it was removed completely due to little or no effect on the behaviour on the model. Only one stock (*Perceived Stress Adjustment*) and one flow (*Perceived Stress Adjustment*) was removed. This is the only part that made the behaviour change slightly from the Vensim1 model. All the variables in the loop ended up only affecting *Potential Work Rate*. It made little impact on *Potential Work Rate* since *Potential Work Rate* was quite high (between 26-38) and *Task Deduction Ratio* (which was the last variable in the *Perceived Stress Adjustment* and *Perceived Stress Adjustment* loop) only varied from (1 to 1.047) which was multiplied in *Potential Work Rate*s equation, in other words only a minor change in *Potential Work Rate*.

To begin with there were 80 variables, but after the simplification the number of variables were reduced to a total of 59 which is a reduction of 74%. The most impressive is that the behaviour only had minor changes. See Figure 4.4, 4.5, 4.6 and 4.7, for a comparison of the models behaviour before and after the simplification. Appendix C can be viewed for greater details on how the model looks after the simplification, see Vensim1 model in Appendix B.1 for comparison.

Table 4.1: List of Simplification Variables (1 of 2)

Variable	Change
AERAT	This constant was added into *AEAR*
D Switch	This variable was removed since it's for test purpose only. *D Switch* had the property of calibrating the *Desired Work Rate*
Effect of CLP on Innovation	This was merged into *Local Innovations and Changes*
Effect of KR on EDR	Removed due to removal of *Knowledge Redundancy*
Effect of KR on MU	Also removed due to removal of *Knowledge Redundancy*
Effect of Performance Pressure on Cognitive Load	*Actual Work Rate* and *Desired Work Rate* are connected to *Cognition Resource Allocation* directly with out the extra variable table that gives the same output as input
Effect of Senior Junior Percentage on Error Rate	Removed due to removal of *Senior Junior Team Members*
Effect of Senior Junior Percentage on Work Rate	Removed due to removal of *Senior Junior Team Members*
Error Detection Skill Normal Increase Rate	This was merged into *EDS Increase*
Increased EDS per Corrected Error	This constant was added into *EDS Increase*
Innovation Knowledge Redundancy Function	Removed due to removal of *Knowledge Redundancy*
Knowledge Redundancy	Removed due to removal of *Senior and Junior Team Members*

Table 4.2: List of Simplification Variables (2 of 2)

Task Deduction Ratio	This variable had little impact on the behaviour of the model, and was therefore removed. The impact was less than 5%
Task Stress Function	
Pressure from Performance Gap	
PSAT	All these variables were only affecting *Task Deduction Ratio* and were therefore removed
Perceived Stress Adjustment	
Perceived Performance Pressure	
Shared MU Adjustment	This was merged with *Increase of Mutual Understanding*
Required Effort for Each Computation	This table multiplyed the input with 0.005, therefore 0.005 was inserted into *CCRA* and *Effect of Cognitive Load on CL Pressure* directly
Senior and Junior Team Members	It was decided to remove this variable since it only adds more complexity to the model, and because it's difficult to predict the ratio between *Senior and Junior Team Members*.

4.3.2   Rebuilding The Vensim1 Model

To rebuild the model the stock and flows from the Vensim2 model (Section 4.3.1) was used as a base. Then one and one variable was carefully added to the model (Vensim3 Table 1.1) while all the time keeping in mind the knowledge gained in Section 4.3.1. The biggest difference between the rebuilt model(Vensim3) and the first simplification(Vensim2) is the removal of the stock and flow *Error Detection Skill* and *EDS Increase*. They turned out to have little impact on the behaviour. Comparing Vensim3 and Vensim1 model shows that there are only 50 variables in Vensim3 and 80 in Vensim1, which makes Vensim3 63% of Vensim1.

See Figure 4.4, 4.5, 4.6 and 4.7, for a comparison of the models behaviour before and after the simplification. Appendix D.1 can be viewed for greater details on how the model looks after the simplification, see the Vensim1 model in Appendix B.1 for comparison.

4.3.3 Model Comparison
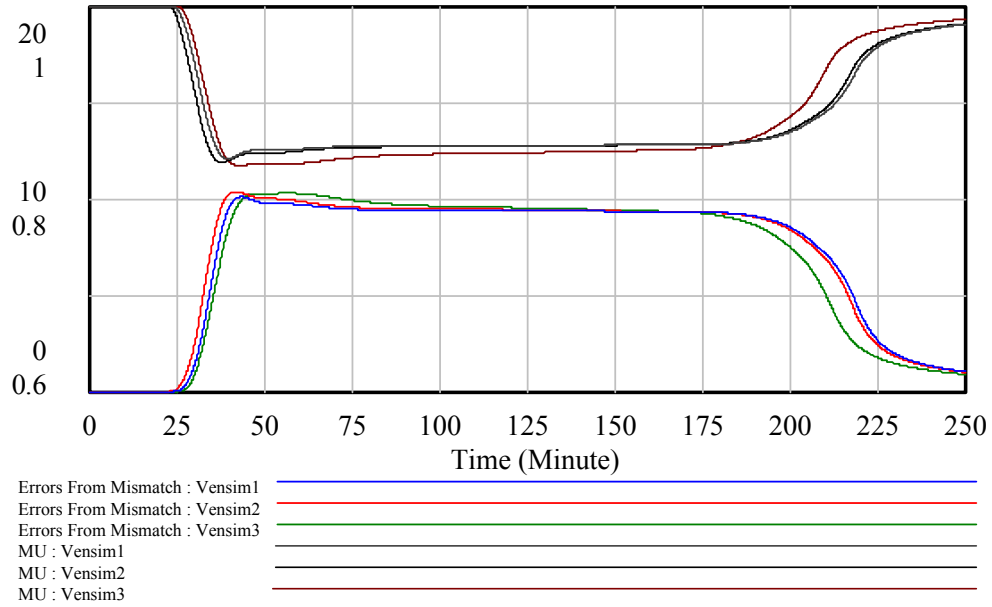
Figure 4.4: Comparison 1 of Vensim1, Vensim2 and Vensim3
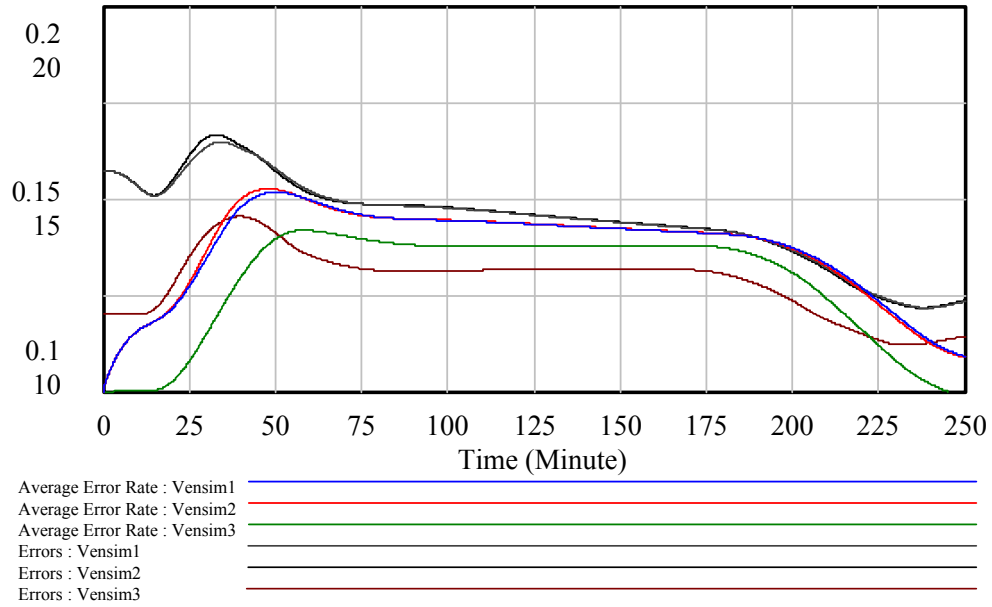
Figure 4.5: Comparison 2 of Vensim1, Vensim2 and Vensim3
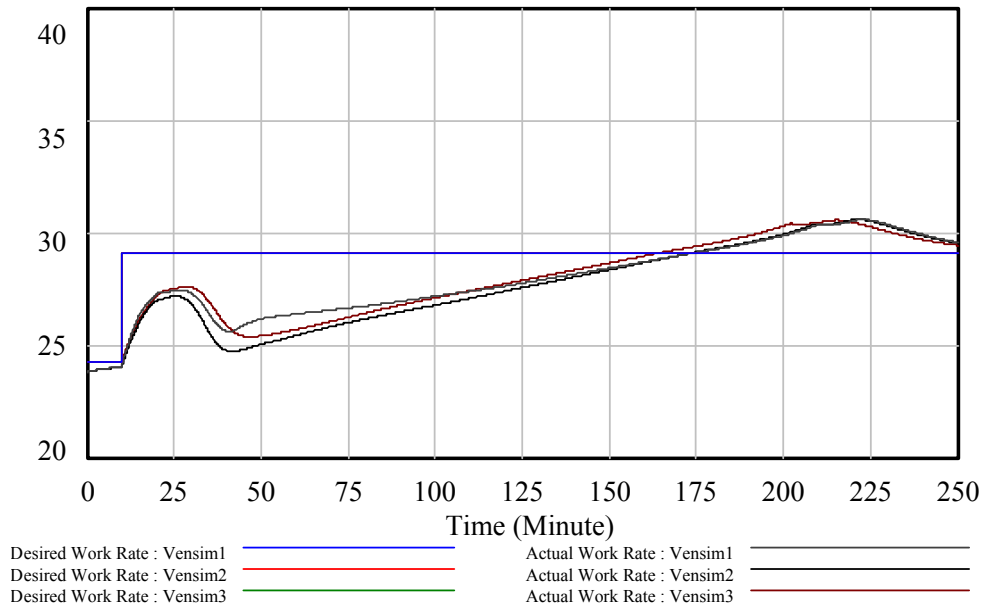
Figure 4.6: Comparison 3 of Vensim1, Vensim2 and Vensim3
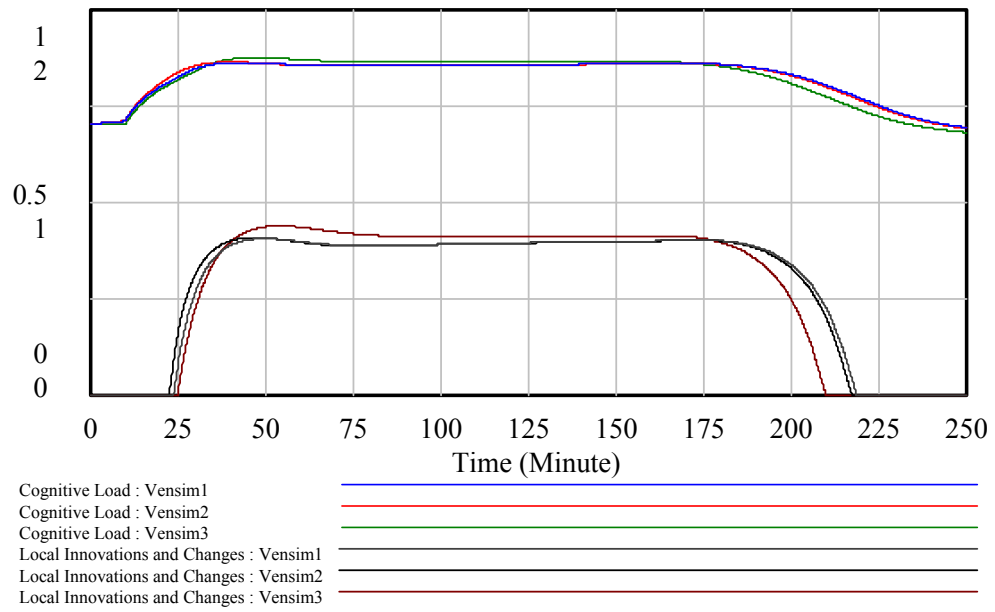
Figure 4.7: Comparison 4 of Vensim1, Vensim2 and Vensim3

4.3.4 Model Testing

To be able to use this model on a real case we need to perform equal test as on Vensim1 model (Table 1.1). In this test we have less variables because of the removed variables. Table 4.3 shows the variables used in this sensitivity test.

Table 4.3: Sensitivity Experiments for Testing Parameters in the Palau-case

Variable	Base case values	10% increase	10% decrease
CAT	10	11	9
COEAT	10	11	9
CCRAT	5	5.5	4.5
CLSAT	5	5.5	4.5
MUDAT	3	3.3	2.7
Normal EGR	0.1	0.11	0.09
Total ManPower	8	8.8	7.2
Senior Junior Team Members	0.5	0.55	0.45

The graphs 4.8, 4.9, 4.10, and 4.11 shows that the behaviour of the rebuilt model (Vensim3) gives the same behaviour as the original model (Vensim1). There are some differences in *Actual Work Rate* which gives a minor delay compared with the other graphs. We conclude that Vensim3 and Vensim1 have equal behaviour, see comparison in the sensitivity graphs in Section 3.5.
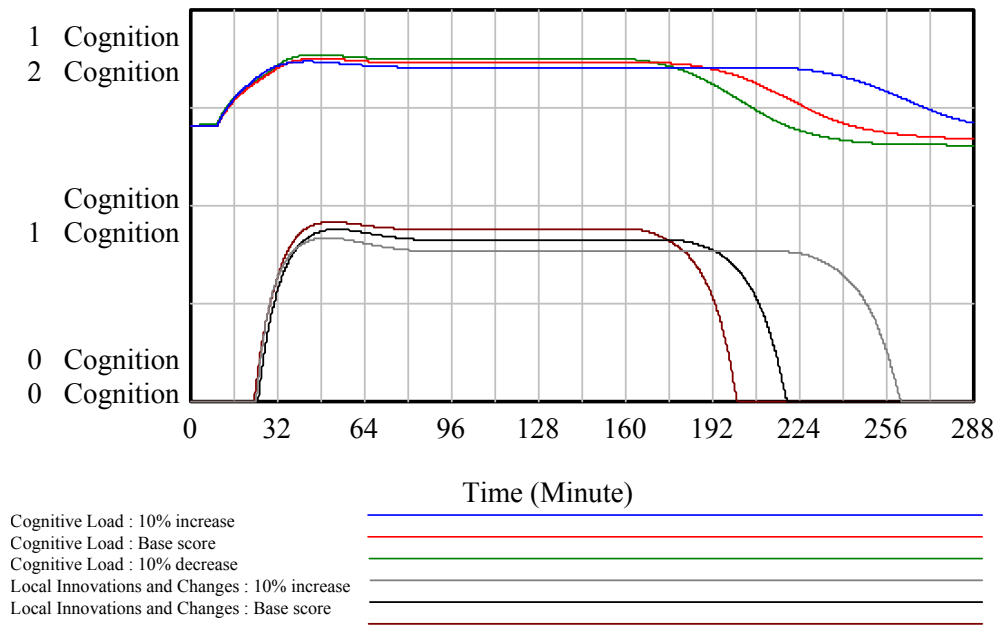
Figure 4.8: Sensitivity Graph Vensim3 Model
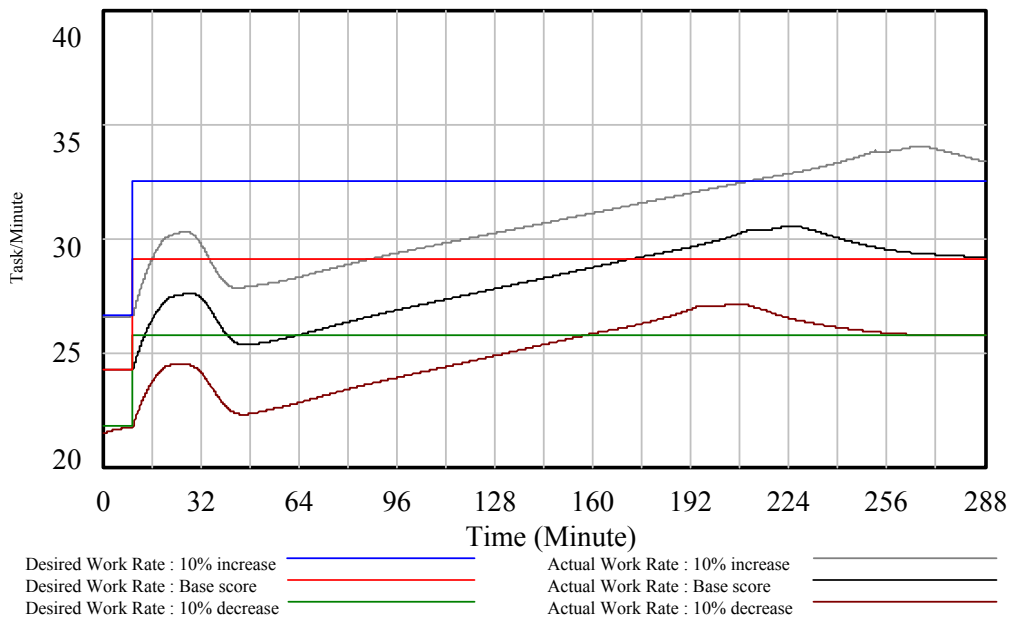
Figure 4.9: Sensitivity Graph Vensim3 Model

Figure 4.10: Sensitivity Graph Vensim3 Model
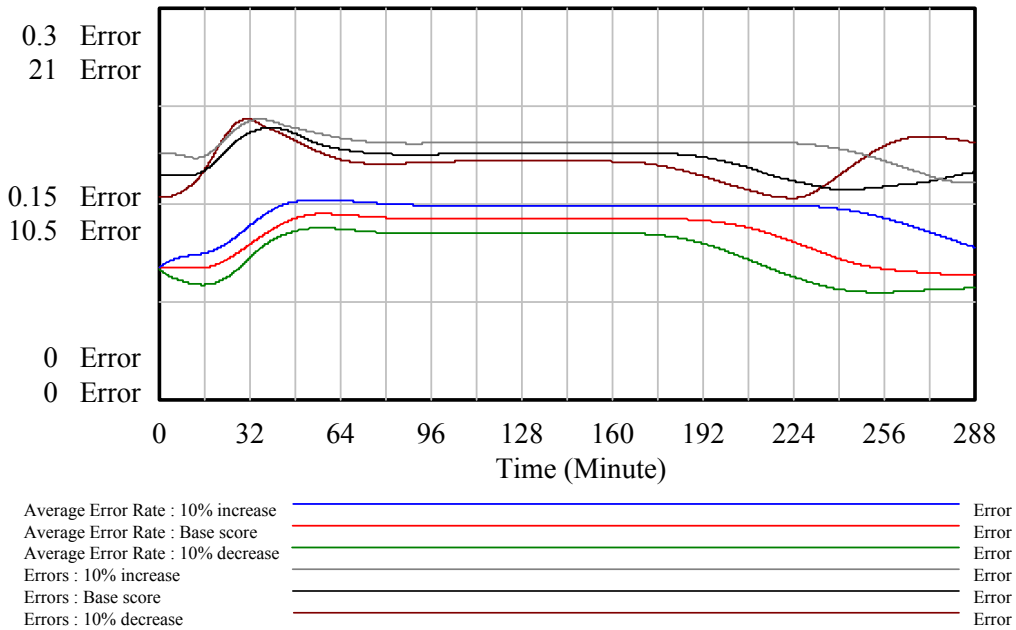
Figure 4.11: Sensitivity Graph Vensim3 Model

Chapter 5

Case

5.1 Case selection

In the case selection process the goal was to find a case that could relate to the self-organizing model we already had simplified, in terms of finding similarities in the variables so it could be applied. The most important factor was that the case had the same behaviour as the *The Palau incident* [4] going from chaos to self-organizing.

In order to find a case Professor Gonzalez proposed a book called *Organisering, samfunnssikkerhet og krisehåndtering* [9] which is a rather new book containing a number of Norwegian crisis incidents. Five different cases from the book were considered; *The E.coli-case, The Tsunami Disaster, Server-Accident, The Giardia-case and The Hatlestad-case*. The book describe the cases from start to finish with details of what happended.

The Hatlestad-case concerns a mudslide that happened in Bergen (in Norway) 14th of September 2005. This happened due to heavy rain in the area which made the earth muddy and unstable. The area also lacked security measures to prevent

this from happening. Three people in total died in the accident and ten people was injured, and many lost their homes. The case was much debated in the media due to the lack of security measures in the area, and who to blame for this. [10, p.1]

After reading carefully through all the chapters we decided to use *The Hatlestad-case* [9, p.216-234]. *The Hatlestad-case* was chosen because the behaviour went from chaos to self-organizing, and the time-dependence of several crucial variables nevertheless is different from the *The Palau incident* [4]. The relative low complexity level in the Hatlestad case made it more attractive to alternative choices and made this case well suited for our purpose of successfully applying the case to the self-organizing model.

5.2 Behaviour of the Hatlestad-case

5.2.1 Timeline

The incident started 14th of September 2005 at 1.54 AM.

" The 14. September 2005 at 1.54 AM Bergen fire department received a message about a mudslide in Hatlestad-terrace. The fire department then notified Hordaland police department , Bergen municipality emergency response team and the civil defence forces. The National Guard was at voluntary disposal." [9, p.219]

The incident ended 14th of September 2005 at 12.00 AM.

"12.00 AM, 14th of September 2005, the urgent phase of the operation was ended" [10, p.60]

Table 5.1: Crisis Management Timeline [10, p.60]

01.54	The fire department was alerted about the incident
01.58	The police was alerted
02.02	AMK received message about the need for health personal
02.05	The police arrived at the incident location
02.20	Helicopter ambulance arrived with doctor
02.20	Civil defence arrived
03.00	Management Officer received message about the incident
03.05	The evacuated people was transported away from the disaster area
03.28	The National Guard reported their manpower
03.30	The evacuated people arrived at their destination(Bergen Airport Hotel)
04.00	The National Guard arrived at the disaster area
04.44	The geologist arrived
05.40	The police established an emergency team for the victims families
06.15	The emergency service arrived
10.00	Bergen municipality established a crisis team
10.00 - 12.00	The fire department ended their participation in the operation
12.00	The urgent phase of the operation was ended

5.2.2 Actual Work Rate and Desired Work Rate

In this case we define the Work Rate as $\frac{Task}{Minute}$, $1\frac{Task}{Minute}$ equals the maximum amount of tasks one worker can perform in one minute. *Normal Amount of Computing Tasks = ManPower*, and *Normal Work Rate = Normal Amount of Computing Tasks* * (1- *Communication Overhead*). The *Communication Overhead* will be greater than in the Palao-case since there are up to 57 workers in the Hatlestad-case compared to only 8 in the Palao-case.

After approximately two hours *"at 04.00 the site of injury was under controll, and there was good overview, and enough resources and personnel"*[10, p.64]. Due to this we assume that the Desired Work Rate equals to the Actual Work Rate at this point (*Desired Work Rate* = 47 from Table 5.2). See Graph 5.1.

It's unknown how much *Communication Overhead* there is but from our knowledge from the Palao-case we know how much *Communication Overhead* there are for up to 10 workers (communication overhead for 10 woerkers = 0.2). Due to the fact that there are about 5 times as many workers in the Hatlestad-case we should at least expect the double amount of *Communication Overhead* when reaching its peak 57 (Table 5.2) workers. The *Local Innovations and Changes* increases the Work Rate and the prediction is that the *Local Innovations and Changes* will equalize the Work Rate lost due to *Communication Overhead*.

Table 5.2: Hatlestad ManPower Estimation done by analyzing the Hattlestad-case, some assumptions are done due to lack of detailed information. For instance instead of number of persons they say the number of cars [9, p.216-234].

Time in Minute	ManPower (number of persons)	Total ManPower(total number of persons)
0	0	0
11	4 Policemen (2 police cars)	4
15	12 Fire-fighters (estimated)	16
20	8 Policemen	24
26	9 Paramedics, and 8 Civil Defence Officers	41
114	6 Extra Personnel	47
480	10 fom the National Guard arrived	57
600	The Fire-fighters has left the area	45

Actual Work Rate starts with an increase :*"02.05 the police force arrived at the site of injury and immediately started an operation center"* [10, p.63]. The *Actual Work Rate* continues to increase as more and more people from different emergency departments arrive at the disaster area. *"02.20 the ambulance and ambulance helicopter arrived at the site of injury and received a message regarding an unconscious person"* [10, p.63], and *"After the first 20 minutes into the mudslide 6 police squads with a total of 12 people had arrived at the site of injury."* [10, p.64]. *"Extra firemen were gathered to increase the work force"* [10, p.64] shows that they increase the workforce over time, and this leads to an increase until the end. The *Actual Work Rate* decreases between 10 AM to 12 AM as the fire department leave the area. *"Between 10.00 - 12.00 AM, the fire department ended their participation since all the missing persons had been found."* [10, p.73]
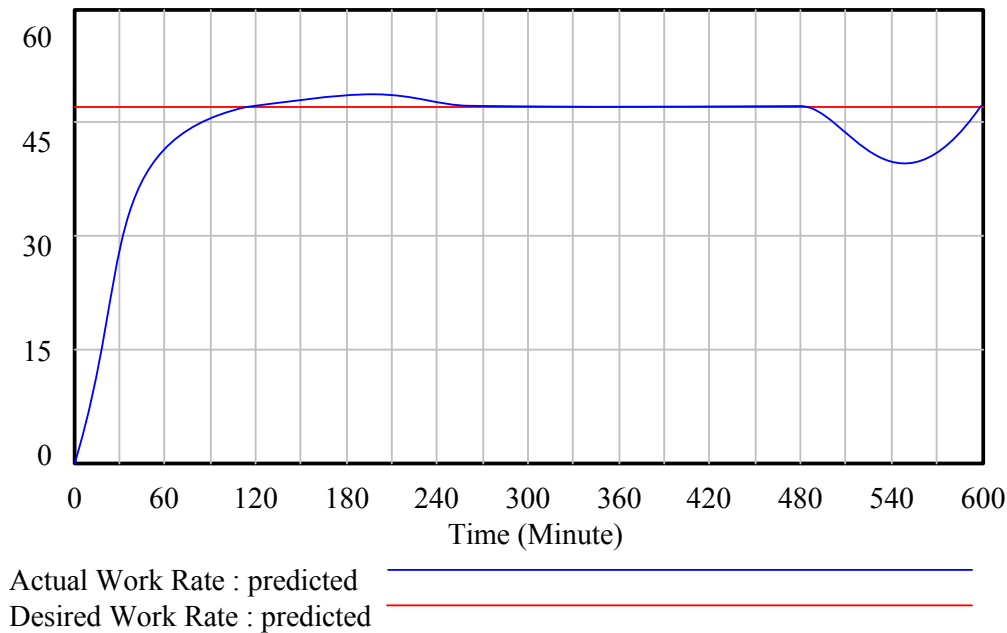
Figure 5.1: Actual Work Rate and Desired Work Rate

5.2.3 Cognitive Load and Local Innovations and Changes

The scale of *Cognitive Load* and *Local Innovation and Changes* varies between 0 and 1, where 0 is no *Cognitive Load* and no *Local Innovation and Changes*, and 1 is 100% *Cognitive Load* and 100% *Local Innovation and Changes* among the rescue people.

The *Cognitive Load* starts to increase when the police arrive at the site of injury. *"02.05 the police force arrived at the site of injury and immediately started an operation center"* [10, p.63].[1] At 02.20 when *"02.20 the ambulance and ambulance helicopter arrived at the site of injury and received a message regarding an unconscious person"* [10, p.63] the *Cognitive Load* increases even more.

We assume *Cognitive Load* and *Local Innovation* will reach its peak before

---

[1]We assume the workers have a pretty high *Cognitive Load* since they are allready on duty, and estemate it te be around 70%

Desired Work Rate is reached, *"at 04.00 the site of injury was under controll, and there was good overview, and enough resources and personnel"* [10, p.64].

The operation seems to be based on some great deal of improvising (*Local Innovation and Changes*): *" Even if the organizing between the emergency staff were following normal procedures, the situation was so extraordinary that the tasks and roles were changed. The informers claimed that this involved improvisation."* [10, p.100].

At *"at 04.00 the site of injury was under controll, and there was good overview, and enough resources and personnel"* [10, p.85] *the Cognitive Load* and *Local Innovation and Changes* decreases. Now that the situation is under control *Local Innovation and Changes* will not occur any more, and will return to 0. This is based on enough workforce on the site of injury, and less pressure to find solutions to the problems at hand. As the rescue teams get more control the *Cognitive Load* decrease. *"Between 10.00 - 12.00 AM, the fire department ended their participation since all the missing persons had been found."* [10, p.73] Which indicates that the *Cognitive Load* will increas a bit for the other resque teams. *Cognitive Load* increase until it reaches about 0.70 (70%) the same as before the incident started.
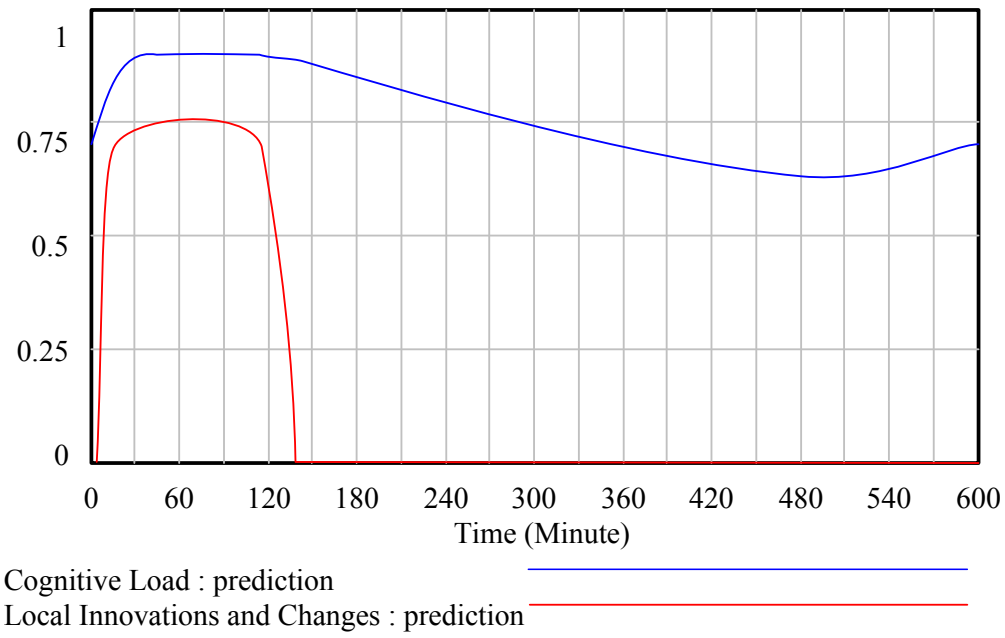
Figure 5.2: Local Innovation and Changes and Cognitive Load

5.2.4 Mutual Understanding

We define the scale of *Mutual Understanding* to be between 0 and 1, where 0 (0%) is no *Mutual Understanding* among the rescue people and 1 (100%) is full *Mutual Understanding*. This is the same percentage scale that were used by Tu et al. on the Palao-case [3].

At the start of the incident the *Mutual Understanding* is high, this is mainly because the communication between the emergency departments are good to begin with, *"In the beginning the emergency services had contact with each other, mainly to notify each other about the situation"* [11]. The "Mutual Understanding" quickly decreases since the communication between the teams is weak throughout the incident, *"The coordination between the different emergency teams can be described as weak. The emergency staffs worked good on the site of injury, but lacked the control of what the others were doing, and their access to resources."* [12, p.14] We estimate the the *Mutual Understanding* to start at 1, but as soon as the Actual Work Rate increase the *Mutual Understanding* will drop down. The Mutual Understanding in the individual teams were good, but they did lack control of what the other rescue teams were doing. When the different teams start with *Local Innovations and Changes* and find new methods to accomplish tasks the *Mutual Understanding* decrease even more since the other teams don't know the methods [3, p.145]. The Mutual Understanding will decrease along with the increase of *Local Innovations and Changes* and increase as the *Local Innovations and Changes* goes down. In this period we assume the *Mutual Understanding* will not go any lower than 0.8 since the teams still knows the essence in what the other teams are doing. *Mutual Understanding* will increase to 1 at the end of the incident.
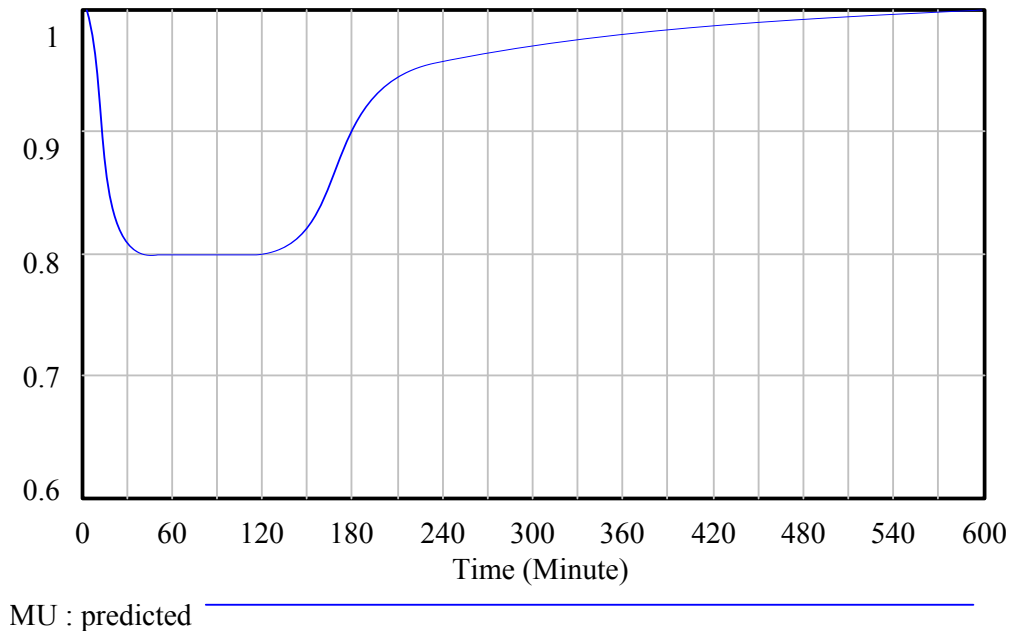
MU : predicted

Figure 5.3: Mutual Understanding

5.3 Implementation of the Hatlestad-case

The implementation of the Hatlestad-case was implemented in the Vensim3 model (Table 1.1). The model was created from the data extracted from the predicted behaviour analysis performed in Section 5.2. It is important to note that the Hatlestad-case did not mention anything about the errors that were caused by the rescue parties. We decided therefore to use the same error rate as Tu et al. used in the Palao-case [4], which gave an indication of how the error rate could be in the Hatlestad-case.

When implementing the Hatlestad-case into the Vensim3 model, we found the model was not optimized to be used with a variable *Total ManPower*, which was originally a constant in the Palao-case. This made the *Actual WorkRate* give somewhat spiky graphs, and not the smooth graphs that were predicted.

Therefore the *Total ManPower* had to be made into a stock and flow in order
to get smoother and more easy to read graphs. The *Total ManPower* which was
a constan-input has now been made into a stock and flow with the inputs *Desired
MP* which are the people that participated in the Hatlestad-rescue (See Table 5.2).
The *Desired MP* were changed by using the STEP function in Vensim. The *Time
to allocate MP* was added since it takes time for the rescue teams to arrive at the
disaster area. It's only known how long time the first police squad and the fire
department used to arrive at the disaster area, which was 7 minutes for the police
(Table 5.1) and 15 minutes for the fire department (Table 5.2). *Time to allocate
MP* was therefore set to 10 (minutes). See Figure 5.4 of the new *Total ManPower*
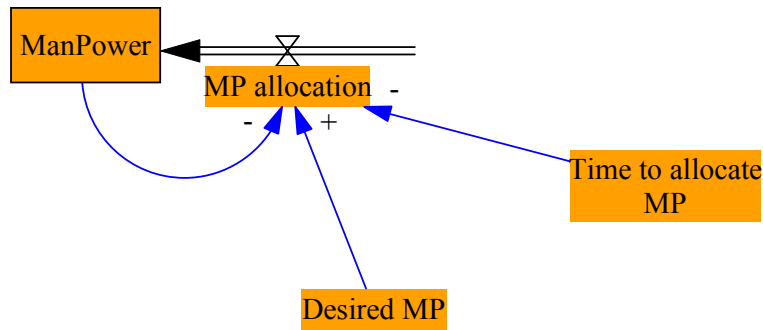
Figure 5.4: *Total ManPower* Converted to Stock and Flow

Comparison of the predicted behaviour and the simulation done in Hatlestad1 (Table 1.1) can be seen in Figure 5.4 below. The figure shows that the predicted graphs have the same behaviour as the one simulate in the Hatlestad1 model. The *Desired Work Rate* are of course identical since it a constant that was set. *Actual Work Rate* is a bit choppy in Hatlestad1, but has the same behaviour, and the predicted goes a bit to much down at the end.

Desired Work Rate : Hatlestad Simulation
Desired Work Rate : predicted
Actual Work Rate : Hatlestad Simulation
Actual Work Rate : predicted
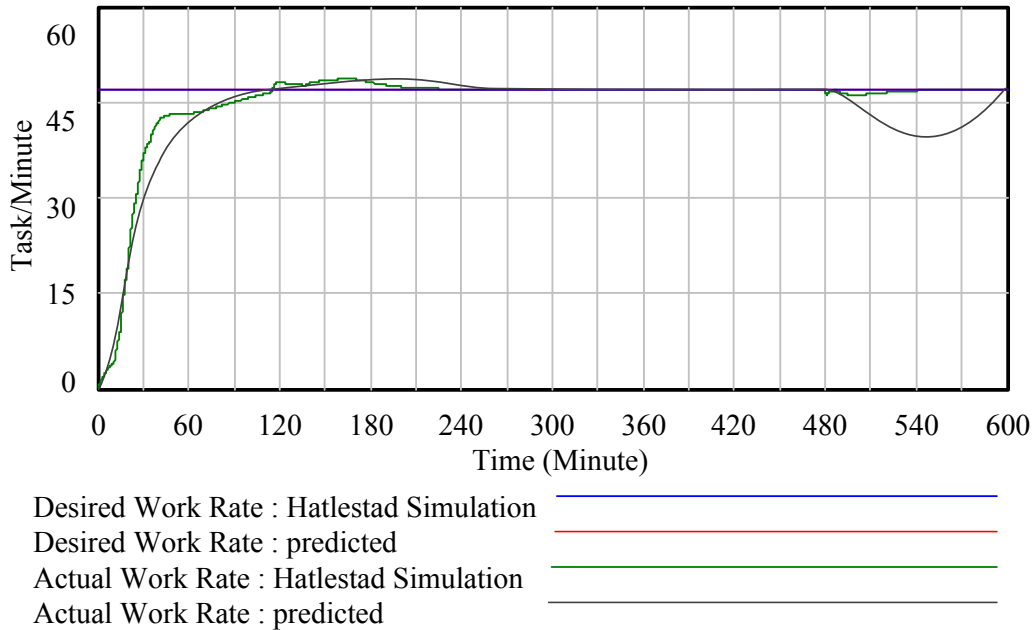
Figure 5.5: Desired Work Rate and Actual Work Rate in The Hatlestad-case

The *Cognitive Load* (see Figure 5.6) are pretty similar to each other but, Hatlestad1 are more flat between 240-480 minutes, which in hindsight seems more logical than what was predicted. *Local Innovations and Changes* look similar except that it has two peaks instead of one curve, and Hatlestad1 goes a bit higher at its peaks than the predicted curve. Hatlestad1 does also go down about 20 minutes later than predicted.
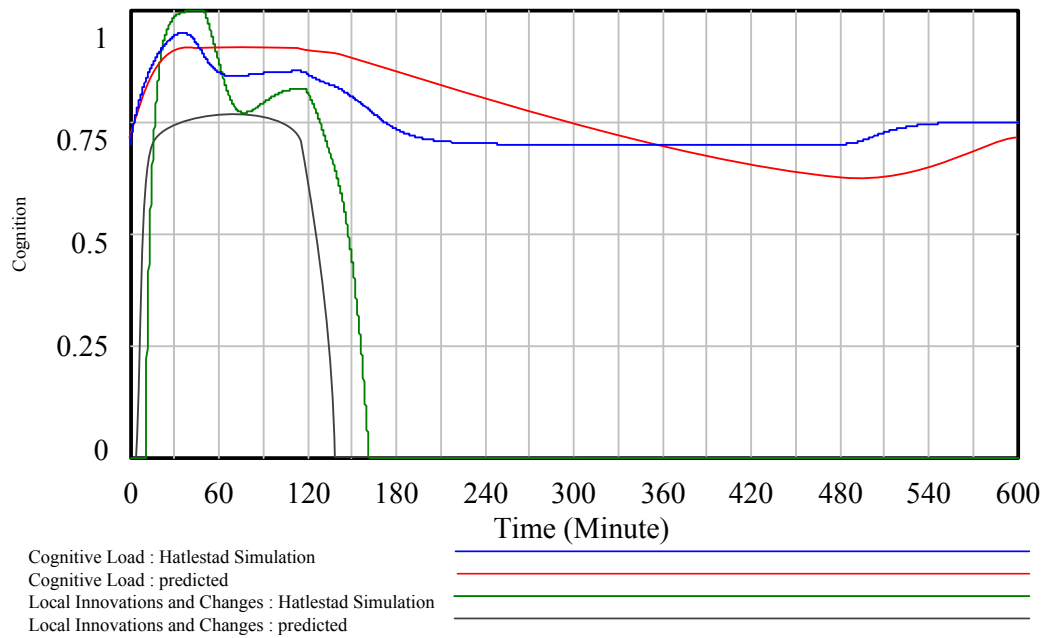
Figure 5.6: Cognitive Load and Local Innovations and Changes in The Hatlestad-case

The *Mutual Understanding* (see Figure 5.7) have the same behaviour in Hatlestad1 and the predicted. The difference are that Hatlestad1 has a little bit higher *Mutual Understanding* from 30 minutes troughout the simulation. Hatlestad1 is also a bit choppy between 20-60 minutes, this is probably due to the *Actual Work Rate* which is not as smooth at this point.

MU : Hatlestad Simulation
MU : predicted
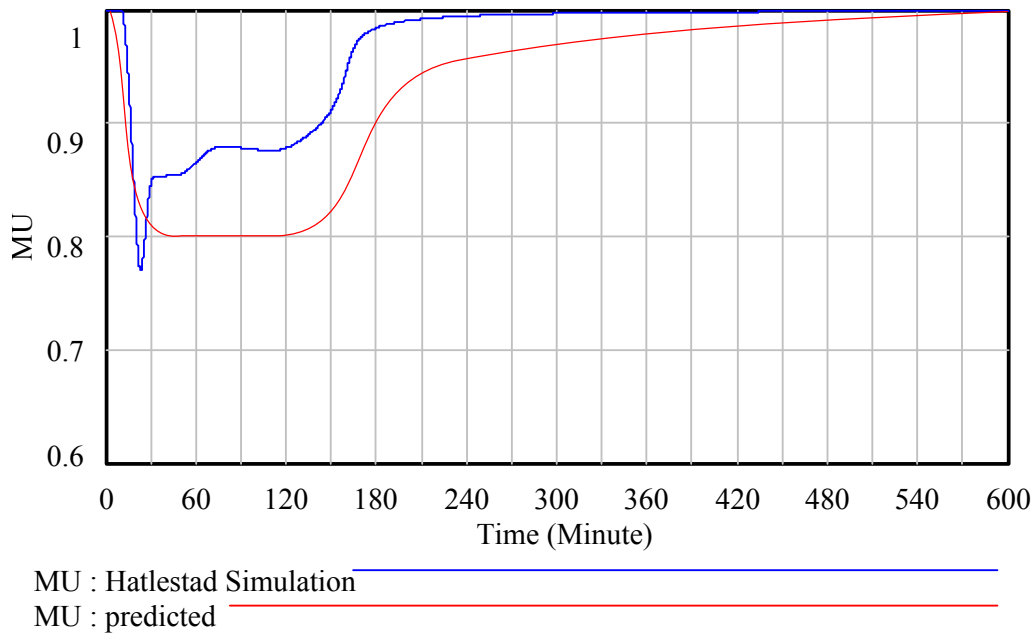
Figure 5.7: Mutual Understanding in The Hatlestad-case

Chapter 6

Conclusion

6.1 Concluding Remarks

The main goal in this work was to create a new more simplified system dynamics model based on Tu et al.'s model on disorganization in a disaster case. The new model was designed to behave similarly, but based on substantial simpler routines.

Relating this to section 1.2 the following was accomplished.

- A new less complex model has been designed and implemented in Vensim

- Tu et al.'s model has been reviewed, with proposals for improvements.

- Units and polarity have been implemented into the model

- The rebuilt model (Vensim3/Hatlestad1) has been implemented on a new different disaster case.

We conclude that the simplified model can be used for better planning in crisis management and can be used to simulate the disorganization in several crisis situ-

ations. The model is easy to understand, and can be used to express the underlying conditions in a crisis situation.

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Appendix A

iThink Model

A.1   Model

Cognitive Load 2
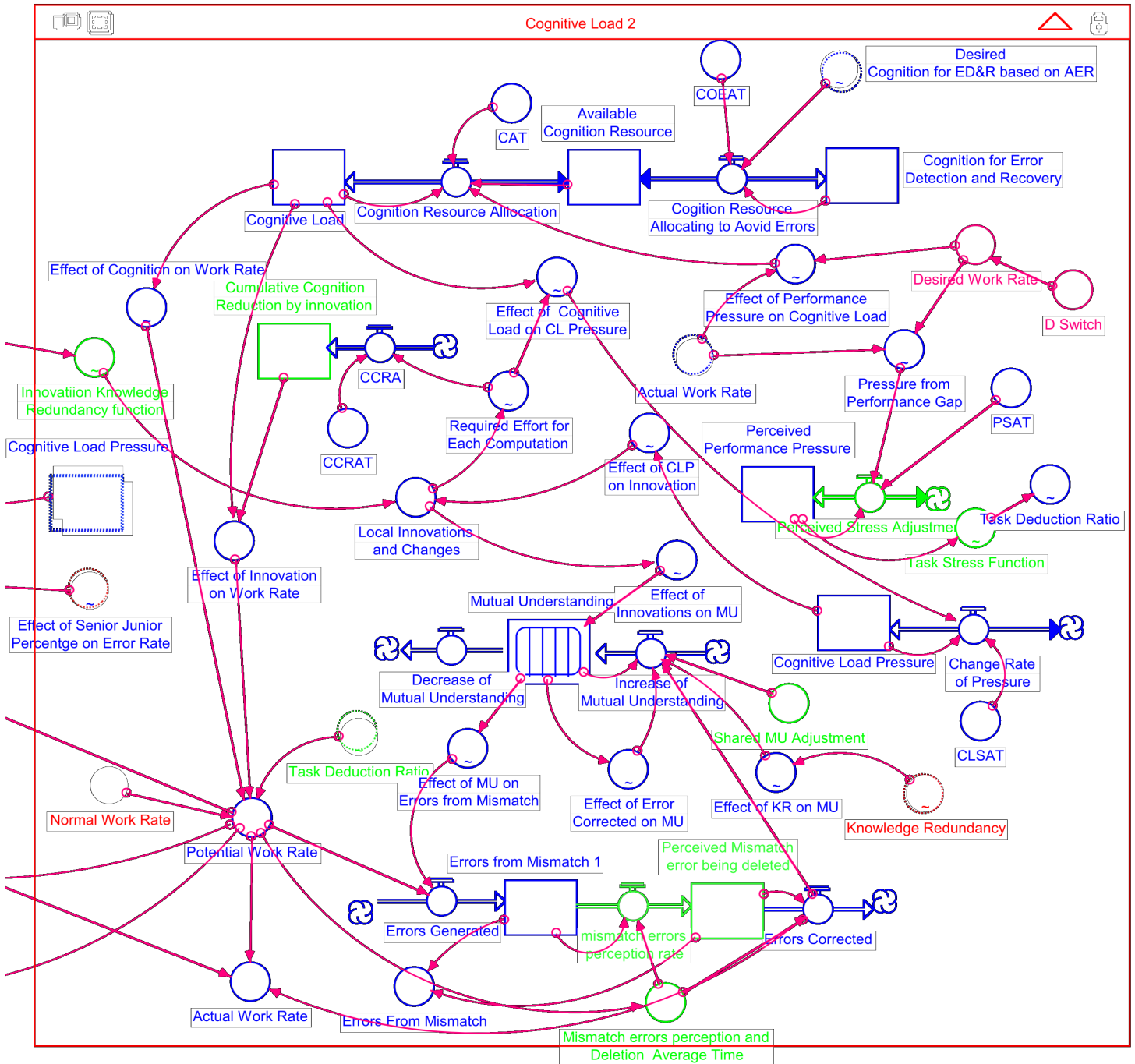
Appendix B

Vensim1 Model

B.1   Model

Effect of Senior Junior
Percentage on Error Rate

Knowledge
Redundancy

Effect of Senior Junior
Percentage on Work Rate

Normal Work
Rate

-

+

+

+

-

+

Senior and Junior
Team Members

Communication
Overhead

Normal Amount of
Computing Tasks

+

+

Total ManPower
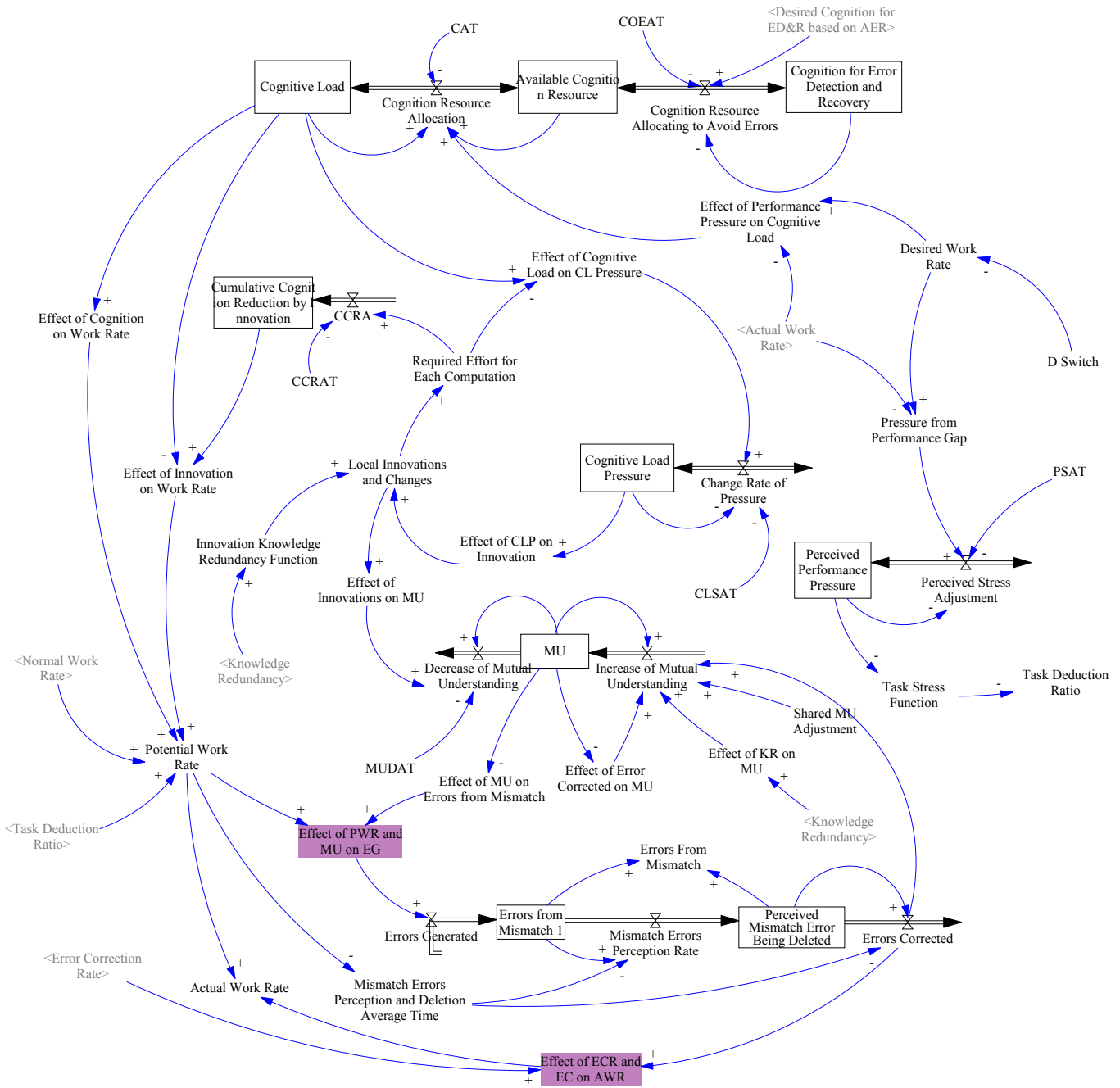
B.2   Equations from Vensim1

```
Actual Work Rate=
        Potential Work Rate-Effect of ECR and EC on AWR
        ˜       Task/Minute
AEAR=
        ((Error Correction Rate/Effect of PWR on Error Rates)-Effect of Average Error Rate on AEAR\
                )/AERAT
        ˜       Error/Minute
Effect of ECR and EC on AWR= WITH LOOKUP (
        Errors Corrected+Error Correction Rate,
                ([(-10,-10)-(10,10)],(-10,-10),(10,10) ))
        ˜       Task/Minute
Effect of Average Error Rate on AEAR= WITH LOOKUP (
        Average Error Rate,
                ([(0,0)-(1,1)],(0,0),(1,1) ))
        ˜       Error/Minute
PSAT=
        10
        ˜       Minute
Effect of PWR and MU on EG= WITH LOOKUP (
        Effect of MU on Errors from Mismatch*Potential Work Rate,
                ([(0,0)-(10,10)],(0,0),(10,10) ))
        ˜       Error/Minute
Mismatch Errors Perception and Deletion Average Time= WITH LOOKUP (
        3*20/Potential Work Rate,
                ([(0,0)-(10,10)],(0,0),(10,10) ))
        ˜       Minute
Errors Generated=
        Effect of PWR and MU on EG
        ˜       Error/Minute
EDS Increase=
        (0.01+Increased EDS per Corrected Error*Error Correction Rate*Error Detection Skill)\
                *Error Detection Skill Increase Function
*Error Detection Skill Normal Increase Rate
        ˜       Error/Minute
Errors= INTEG (
        (Error Generation Rate-Error Correction Rate),
                Error Generation Rate*Average time for Error Correction/Effect of EDR on ECR)
        ˜       Error
Effect of PWR on Error Rates= WITH LOOKUP (
        Potential Work Rate,
                ([(0,0)-(100,100)],(0,0),(10,10),(20,20),(30,30),(40,40),(50,50),(60,60),(70,70),(80\
                ,80),(90,90),(100,100) ))
        ˜       Dmnl
Average time for Error Correction= WITH LOOKUP (
        6*20/Effect of PWR on Error Rates,
                ([(0,0)-(10,10)],(0,0),(10,10) ))
        ˜       Minute
Error Correction Rate=
        (Effect of EDR on ECR*Errors)/Average time for Error Correction
        ˜       Error/Minute
Error Generation Rate=
        Effect of PWR on Error Rates*Effect of CL Pressure on Errors*Normal EGR*Effect of Senior Junior Percentage on Error Rate\
                *"Effect of Cognition for ED&R on Errors"
        ˜       Error/Minute
Effect of EDR on ECR= WITH LOOKUP (
        Error Detection Rate,
                ([(0,0)-(2,2)],(0,0),(0.5,0.5),(1,1),(2,2) ))
        ˜       Dmnl
"Effect of Cognition for ED&R on Errors"= WITH LOOKUP (
```

```
                Cognition for Error Detection and Recovery*Error Detection Skill ,
                      ([(0,0.8)−(0.3,1.2)],(0,1.2),(0.025,1.19),(0.05,1.16),(0.075,1.11),(0.1,1),(0.125,0.934\
                      ),(0.15,0.89),(0.175,0.862),(0.2
                      ,0.838),(0.225,0.82),(0.25,0.81),(0.275,0.804),(0.3,0.8) ))
             ˜        Dmnl
Available Cognition Resource= INTEG (
         (−Cognition Resource Allocation−Cognition Resource Allocating to Avoid Errors),
                   1−Cognitive Load−Cognition for Error Detection and Recovery)
             ˜        Cognition
Effect of MU on Errors from Mismatch= WITH LOOKUP (
         MU,
                   ([(0.3,0)−(1,1)],(0.3,1),(0.37,0.745),(0.44,0.545),(0.51,0.41),(0.58,0.315),(0.65,0.235\
                   ),(0.72,0.175),(0.79,0.12),(0.86,0.075),(0.93,0.03),(1,0) ))
             ˜        Dmnl
Effect of Performance Pressure on Cognitive Load= WITH LOOKUP (
         Desired Work Rate/Actual Work Rate,
                   ([(0,0)−(2,2)],(0,0),(0.2,0.2),(0.4,0.4),(0.6,0.6),(0.8,0.8),(1,1),(1.2,1.2),(1.4,1.4\
                   ),(1.6,1.6),(1.8,1.8),(2,2) ))
             ˜        1
Decrease of Mutual Understanding=
         MU*Effect of Innovations on MU/MUDAT
             ˜        MU/Minute
Cognition Resource Allocating to Avoid Errors=
         ("Desired Cognition for ED&R based on AER"−Cognition for Error Detection and Recovery\
                   )/COEAT
             ˜        Cognition/Minute
Cognition for Error Detection and Recovery= INTEG (
         Cognition Resource Allocating to Avoid Errors ,
                   0.1)
             ˜        Cognition
Cognition Resource Allocation=
         MIN(( Effect of Performance Pressure on Cognitive Load−1)*Cognitive Load, Available Cognition Resource\
                   )/CAT
             ˜        Cognition/Minute
Cumulative Cognition Reduction by Innovation= INTEG (
         CCRA,
                   0)
             ˜        Cognition
CCRA=
         Required Effort for Each Computation/CCRAT
             ˜        Cognition/Minute
Errors Corrected=
         Perceived Mismatch Error Being Deleted/Mismatch Errors Perception and Deletion Average Time
             ˜        Error/Minute
Change Rate of Pressure=
         (Effect of Cognitive Load on CL Pressure−Cognitive Load Pressure)/CLSAT
             ˜        Cognition/Minute
Errors from Mismatch 1= INTEG (
         (Errors Generated−Mismatch Errors Perception Rate),
                   0)
             ˜        Error
Effect of Cognitive Load on CL Pressure= WITH LOOKUP (
         Cognitive Load−Required Effort for Each Computation ,
                   ([(0,0)−(1,1)],(0,0),(0.1,0.02),(0.2,0.055),(0.3,0.115),(0.4,0.21),(0.5,0.34),(0.6,\
                   0.5),(0.7,0.65),(0.8,0.82),(0.9,1),(1,1) ))
             ˜        Cognition
Effect of Error Corrected on MU= WITH LOOKUP (
         MU,
                   ([(0,0)−(1,1)],(0,1),(0.1,0.715),(0.2,0.535),(0.3,0.41),(0.4,0.32),(0.5,0.25),(0.6,\
                   0.185),(0.7,0.13),(0.8,0.08),(0.9,0.035),(1,0) ))
             ˜        1/Error
Required Effort for Each Computation= WITH LOOKUP (
```

```
        Local Innovations and Changes,
                ([(0,0)-(2,0.01)],(0,0),(0.2,0.001),(0.4,0.002),(0.6,0.003),(0.8,0.004),(1,0.005),(\
                1.2,0.006),(1.4,0.00705),(1.6,0.008),(1.8,0.009),(2,0.01) ))
        ~       Cognition
Cognitive Load= INTEG (
        Cognition Resource Allocation,
                0.7)
        ~       Cognition
Cognitive Load Pressure= INTEG (
        Change Rate of Pressure,
                0.65)
        ~       Cognition
Local Innovations and Changes=
        Effect of CLP on Innovation*Innovation Knowledge Redundancy Function
        ~       Cognition
MU= INTEG (
        Increase of Mutual Understanding-Decrease of Mutual Understanding,
                1)
        ~       MU
Pressure from Performance Gap= WITH LOOKUP (
        Desired Work Rate/Actual Work Rate,
                ([(1,0)-(1.15,1)],(1,0),(1.01,0.025),(1.03,0.065),(1.04,0.125),(1.06,0.19),(1.07,0.27\
                ),(1.09,0.355),(1.1,0.475),(1.12,0.63),(1.135,0.815),(1.15,1) ))
        ~       Pressure
Mismatch Errors Perception Rate=
        Errors from Mismatch 1/Mismatch Errors Perception and Deletion Average Time
        ~       Error/Minute
Perceived Stress Adjustment=
        MIN((1-Perceived Performance Pressure)/PSAT , (Pressure from Performance Gap-Perceived Performance Pressure\
                )/PSAT)
        ~       Pressure/Minute
Effect of CLP on Innovation= WITH LOOKUP (
        Cognitive Load Pressure,
                ([(0.8,0)-(1,1)],(0.8,0),(0.82,0.24),(0.84,0.42),(0.86,0.555),(0.88,0.66),(0.9,0.745\
                ),(0.92,0.81),(0.94,0.87),(0.96,0.915),(0.98,0.955),(1,1) ))
        ~       Cognition
Perceived Mismatch Error Being Deleted= INTEG (
        (Mismatch Errors Perception Rate-Errors Corrected),
                0)
        ~       Error
Effect of Innovations on MU= WITH LOOKUP (
        Local Innovations and Changes,
                ([(0,0)-(2,0.5)],(0,0),(0.2,0.0175),(0.4,0.04),(0.6,0.0625),(0.8,0.095),(1,0.133),(\
                1.2,0.185),(1.4,0.24),(1.6,0.32),(1.8,0.407),(2,0.5) ))
        ~       Dmnl
Perceived Performance Pressure= INTEG (
        Perceived Stress Adjustment,
                0)
        ~       Pressure
Effect of Cognition on Work Rate= WITH LOOKUP (
        Cognitive Load,
                ([(0,0)-(1,1.8)],(0,0),(0.1,0.19),(0.2,0.4),(0.3,0.6),(0.4,0.8),(0.5,1),(0.6,1.2),(\
                0.7,1.4),(0.8,1.6),(0.9,1.7),(1,1.8) ))
        ~       Dmnl
Increase of Mutual Understanding=
        (0.01+Errors Corrected*Effect of KR on MU*MU)*Effect of Error Corrected on MU*Shared MU Adjustment
        ~       MU/Minute
MUDAT=
        3
        ~       Minute
COEAT=
        10
```

```
~              Minute
Average Error Rate= INTEG (
        AEAR,
                0.1)
        ~        Error
CAT=
        10
        ~        Minute
CCRAT=
        4
        ~        Minute
Errors From Mismatch=
        Errors from Mismatch 1+Perceived Mismatch Error Being Deleted
        ~        Error
CLSAT=
        5
        ~        Minute
Innovation Knowledge Redundancy Function= WITH LOOKUP (
        Knowledge Redundancy,
                ([(0,0.5)−(1,2)],(0,0.5),(0.1,0.522),(0.2,0.583),(0.3,0.665),(0.4,0.808),(0.5,1),(0.6\
                ,1.22),(0.7,1.44),(0.8,1.71),(0.9,2),(1,2)  ))
        ~        Dmnl
Effect of Innovation on Work Rate=
        1+(Cumulative Cognition Reduction by Innovation/Cognitive Load)
        ~        Dmnl
Potential Work Rate=
        Effect of Cognition on Work Rate*Task Deduction Ratio*Normal Work Rate*Effect of Innovation on Work Rate
        ~        Task/Minute
D Switch=
        0
        ~        Task/Minute
Desired Work Rate=
        24.23+(STEP(24.23*0.2,10))*(1−D Switch)
        ~        Task/Minute
Shared MU Adjustment=
        0.2
        ~        Dmnl
Task Deduction Ratio= WITH LOOKUP (
        Task Stress Function,
                ([(0.8,1)−(1,1.2)],(0.8,1.2),(0.82,1.18),(0.84,1.16),(0.86,1.14),(0.88,1.12),(0.9,1.1\
                ),(0.92,1.08),(0.94,1.06),(0.96,1.04),(0.98,1.02),(1,1)  ))
        ~        Dmnl
Effect of KR on MU= WITH LOOKUP (
        Knowledge Redundancy,
                ([(0,0)−(1,5)],(0,0),(0.1,0.05),(0.2,0.17),(0.3,0.35),(0.4,0.625),(0.5,1),(0.6,1.48\
                ),(0.7,2.2),(0.8,3.02),(0.9,3.92),(1,5)  ))
        ~        Dmnl
Task Stress Function= WITH LOOKUP (
        Perceived Performance Pressure,
                ([(0,0.8)−(1,1)],(0,1),(0.1,0.995),(0.2,0.991),(0.3,0.985),(0.4,0.978),(0.5,0.969),\
                (0.6,0.953),(0.7,0.934),(0.8,0.908),(0.9,0.863),(1,0.8)  ))
        ~        Dmnl
Communication Overhead= WITH LOOKUP (
        Total ManPower,
                ([(0,0)−(10,0.2)],(1,0),(2,0.009),(3,0.02),(4,0.034),(5,0.051),(6,0.074),(7,0.099),\
                (8,0.126),(9,0.161),(10,0.2)  ))
        ~        Dmnl
"Effect of Cognition for ED&R on EDR"= WITH LOOKUP (
        Cognition for Error Detection and Recovery,
                ([(0,0)−(0.3,1.5)],(0,0),(0.0333,0.15),(0.0667,0.44),(0.1,1),(0.133,1.24),(0.167,1.36\
                ),(0.2,1.43),(0.233,1.46),(0.267,1.49),(0.3,1.5)  ))
        ~        Dmnl
```

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AERAT=
        5
        ~   Dmnl
Effect of Senior Junior Percentage on Work Rate= WITH LOOKUP (
        Senior and Junior Team Members,
                ([(0,0.7)−(1,1.3)],(0,0.7),(0.1,0.76),(0.2,0.82),(0.3,0.88),(0.4,0.94),(0.5,1),(0.6\
                ,1.06),(0.7,1.12),(0.8,1.18),(0.9,1.24),(1,1.3)))
        ~   Dmnl
Normal Amount of Computing Tasks= WITH LOOKUP (
        Total ManPower,
                ([(0,0)−(10,40)],(0,0),(1,1),(2,2.25),(3,4.25),(4,7),(5,10.4),(6,14),(7,18),(8,22),\
                (9,26),(10,30)))
        ~   Task/Minute
Error Detection Skill= INTEG (
        EDS Increase,
                0.5)
        ~   Error
Error Detection Skill Normal Increase Rate=
        0.002
        ~   Dmnl
Effect of CL Pressure on Errors= WITH LOOKUP (
        Cognitive Load Pressure,
                ([(0,0)−(1,1.5)],(0,0.8),(0.1,0.802),(0.2,0.81),(0.3,0.818),(0.4,0.833),(0.5,0.87),\
                (0.6,0.95),(0.7,1.05),(0.8,1.19),(0.9,1.34),(1,1.5)))
        ~   Dmnl
Total ManPower=
        8
        ~   Worker
Normal EDR= WITH LOOKUP (
        Error Detection Skill,
                ([(0,0.5)−(1,1)],(0,0.5),(0.1,0.613),(0.2,0.705),(0.3,0.775),(0.4,0.833),(0.5,0.885\
                ),(0.6,0.917),(0.7,0.95),(0.8,0.973),(0.9,0.988),(1,1)))
        ~   Error/Minute
"Desired Cognition for ED&R based on AER"= WITH LOOKUP (
        Average Error Rate,
                ([(0,0)−(0.3,0.3)],(0,0),(0.05,0.051),(0.1,0.1),(0.15,0.15),(0.2,0.2),(0.25,0.25),(\
                0.3,0.3)))
        ~   Cognition
Increased EDS per Corrected Error=
        1
        ~   Dmnl
Normal Work Rate=
        Effect of Senior Junior Percentage on Work Rate*Normal Amount of Computing Tasks*(1−\
                Communication Overhead)
        ~   Task/Minute
Error Detection Skill Increase Function= WITH LOOKUP (
        Error Detection Skill,
                ([(0,0)−(1,1)],(0,1),(0.1,0.73),(0.2,0.545),(0.3,0.4),(0.4,0.3),(0.5,0.215),(0.6,0.15\
                ),(0.7,0.105),(0.8,0.065),(0.9,0.03),(1,0)))
        ~   1/Error
Knowledge Redundancy= WITH LOOKUP (
        Senior and Junior Team Members,
                ([(0,0)−(1,1)],(0,0),(0.1,0.1),(0.2,0.2),(0.3,0.3),(0.4,0.4),(0.5,0.5),(0.6,0.6),(0.7\
                ,0.7),(0.8,0.8),(0.9,0.9),(1,1)))
        ~   Dmnl
Effect of KR on EDR= WITH LOOKUP (
        Knowledge Redundancy,
                ([(0,0.5)−(1,1.3)],(0,0.5),(0.1,0.54),(0.2,0.604),(0.3,0.704),(0.4,0.852),(0.5,1),(\
                0.6,1.14),(0.7,1.22),(0.8,1.27),(0.9,1.29),(1,1.3)))
        ~   Dmnl
Senior and Junior Team Members=
        0.5

~   Worker/Worker
Effect of Senior Junior Percentage on Error Rate= WITH LOOKUP (
        Senior and Junior Team Members,
                ([(0,0.5)-(1,1.5)],(0,1.5),(0.1,1.4),(0.2,1.3),(0.3,1.2),(0.4,1.1),(0.5,1),(0.6,0.9\
                ),(0.7,0.8),(0.8,0.7),(0.9,0.6),(1,0.5)))
            ~   Dmnl
Error Detection Rate=
        Normal EDR*"Effect of Cognition for ED&R on EDR"*Effect of KR on EDR
            ~   Error/Minute
Normal EGR=
        0.1
            ~   Error/Minute
****
        .Control
***~
                Simulation Control Parameters
FINAL TIME = 250
        ~   Minute
        ~   The final time for the simulation.
        |

INITIAL TIME = 0
        ~   Minute
        ~   The initial time for the simulation.
SAVEPER =
        TIME STEP
        ~   Minute [0,?]
        ~   The frequency with which output is stored.
TIME STEP = 0.125
        ~   Minute [0,?]
        ~   The time step for the simulation.

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Appendix C

Vensim2 Model

C.1   Model

Normal Work
Rate

\-

+

Communication
Overhead

+

Normal Amount of
Computing Tasks

+

Total ManPower

Appendix D

Vensim3 Model and Hatlestad1 Model

D.1   Model

Vensim3   Hatlestad1
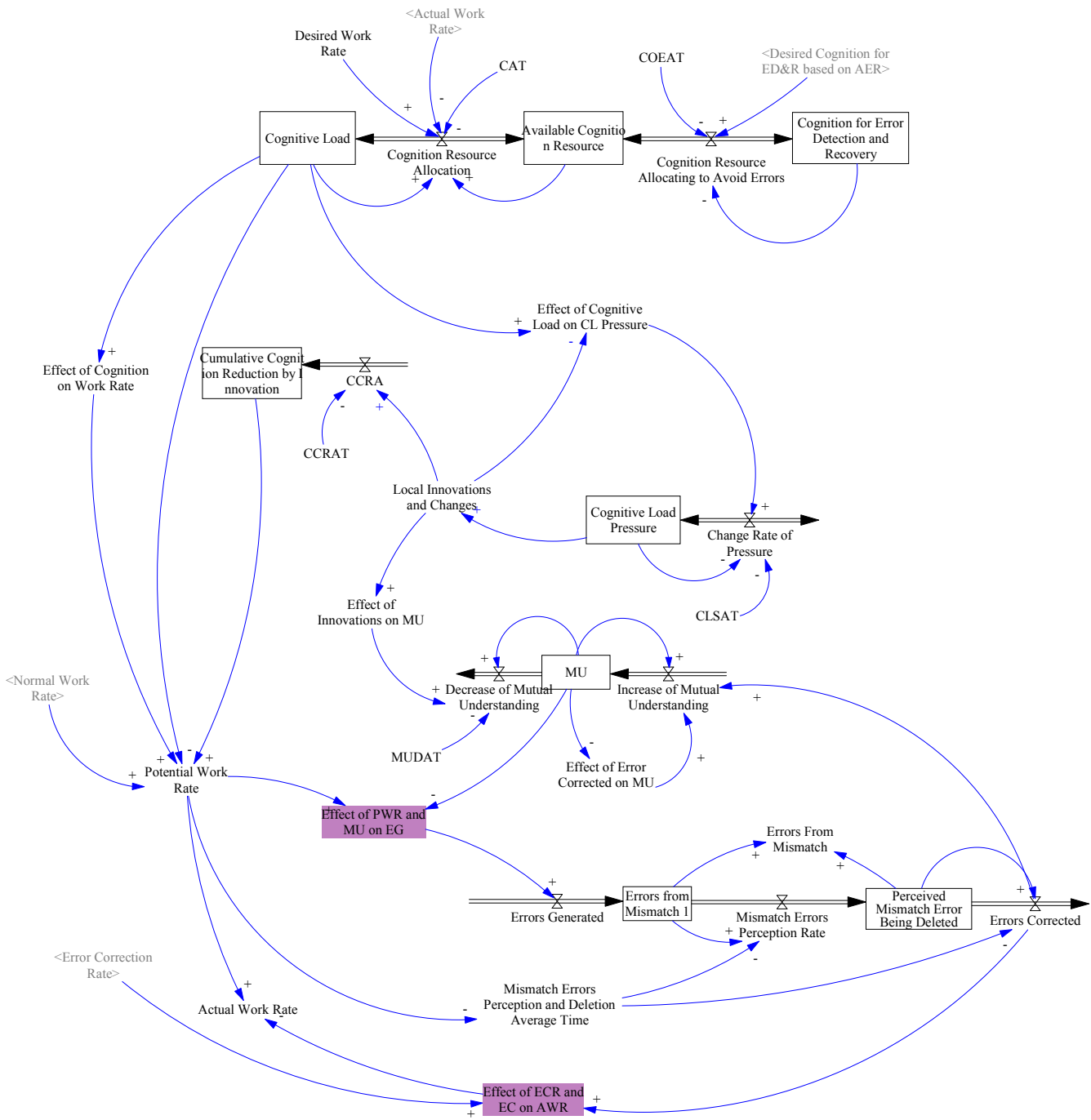
D.2 Equations from Hatlestad1

```
Communication Overhead= WITH LOOKUP (
        ManPower,
                ([(0,0)−(55,0.43)],(0,0),(1,0),(4,0.0264035),(10,0.07),(18,0.122588),(26.9113,0.182939\
                ),(39.1896,0.27),(48.6086,0.36),(54,0.43) ))
        ~       Dmnl
Time to allocate MP=10
        ~       Minute
Desired MP=
        4+STEP( 12, 11)+STEP( 8, 15)+STEP( 17, 20)+STEP( 6, 26)+STEP( 10 , 114 )+STEP( −12 ,\
                480)
        ~       Worker
ManPower= INTEG (
        MP allocation ,
                0.1)
        ~       Worker
MP allocation=
        (Desired MP−ManPower)/Time to allocate MP
        ~       Worker/Minute
Errors= INTEG (
        (Error Generation Rate−Error Correction Rate),
                Error Generation Rate*Average time for Error Correction/
                "Effect of Cognition for ED&R on EDR"\
                )
        ~       Error
Error Correction Rate=
        ("Effect of Cognition for ED&R on EDR"*Errors)/Average time for Error Correction
        ~       Error/Minute
Error Generation Rate=
        Effect of PWR on Error Rates*Effect of CL Pressure on Errors*Normal EGR
        ~       Error/Minute
Potential Work Rate=
        Effect of Cognition on Work Rate*Normal Work Rate*
        (1+(Cumulative Cognition Reduction by Innovation\
                /Cognitive Load))
        ~       Task/Minute
Cognition Resource Allocation=
        MIN(((Desired Work Rate/Actual Work Rate)−1)*Cognitive Load, Available Cognition Resource\
                )/CAT
        ~       Cognition/Minute
Actual Work Rate=
        Potential Work Rate−Effect of ECR and EC on AWR
        ~       Task/Minute
AEAR=
        ((Error Correction Rate/Effect of PWR on Error Rates)−Effect of Average Error Rate on AEAR\
                )/5
        ~       Error/Minute
Effect of ECR and EC on AWR= WITH LOOKUP (
        Errors Corrected+Error Correction Rate,
                ([(−10,−10)−(10,10)],(−10,−10),(10,10) ))
        ~       Task/Minute
Effect of Average Error Rate on AEAR= WITH LOOKUP (
        Average Error Rate ,
                ([(0,0)−(1,1)],(0,0),(1,1) ))
        ~       Error/Minute
Effect of PWR and MU on EG= WITH LOOKUP (
        (1−SQRT(MU))*Potential Work Rate,
                ([(0,0)−(10,10)],(0,0),(10,10) ))
        ~       Error/Minute
Mismatch Errors Perception and Deletion Average Time= WITH LOOKUP (
```
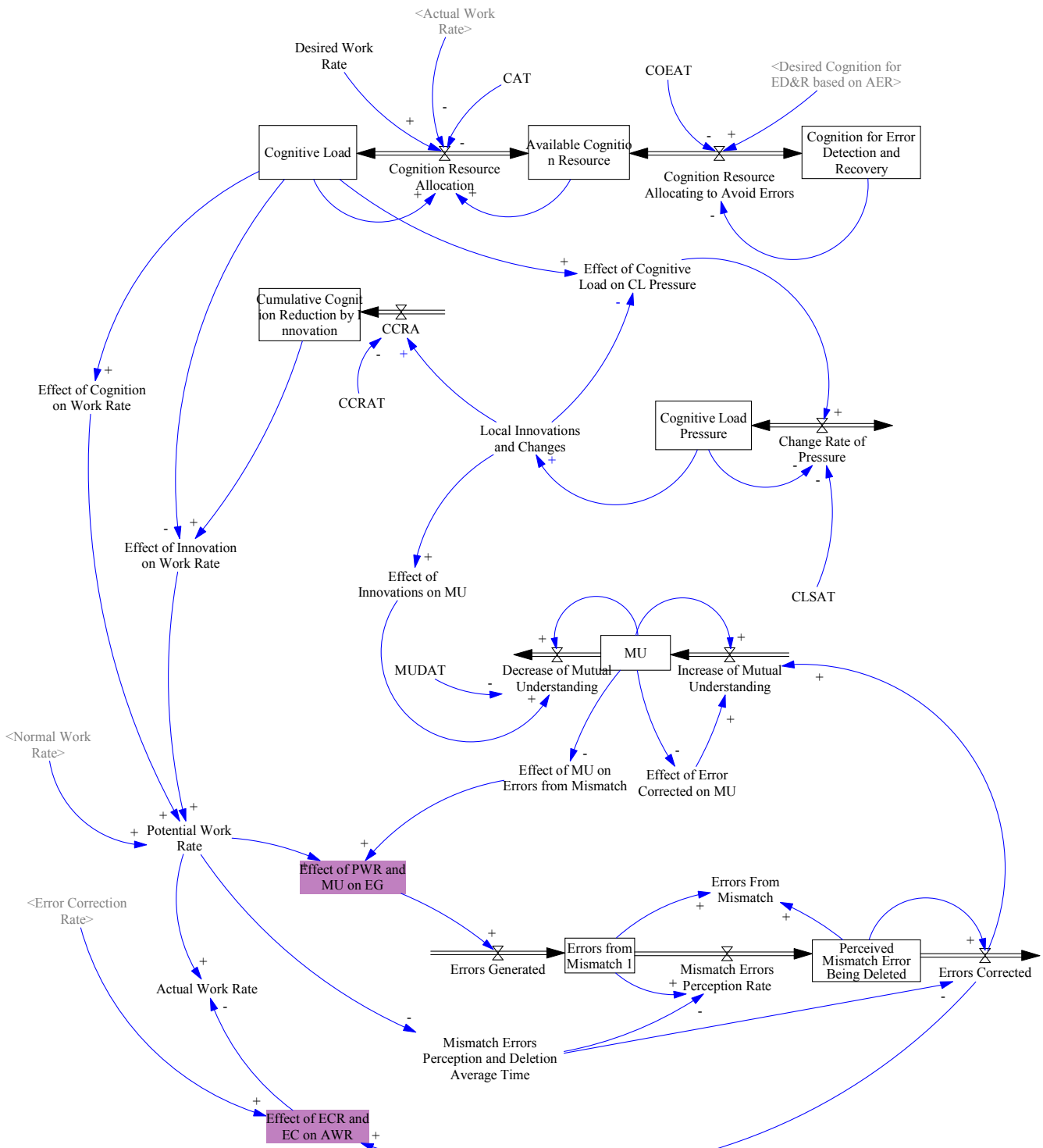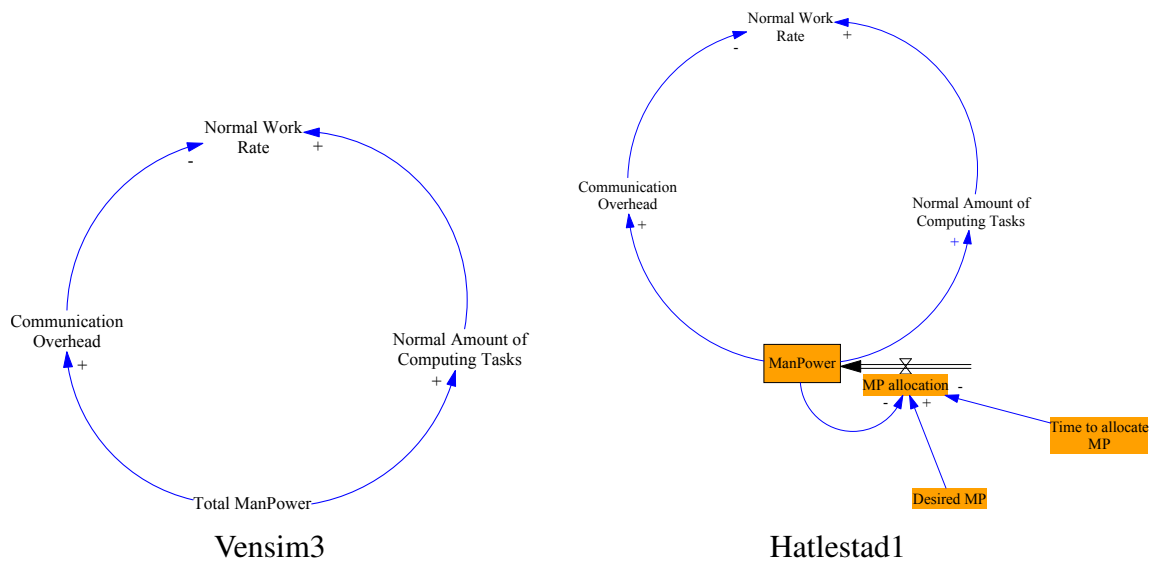
```
              3*20/ Potential Work Rate ,
                    ([(0,0) −(10,10)],(0,0),(10,10) ))
         ~        Minute
Errors Generated=
         Effect of PWR and MU on EG
         ~        Error / Minute
Effect of PWR on Error Rates= WITH LOOKUP (
         Potential Work Rate ,
                    ([(0,0) −(100,100)],(0,0),(10,10),(20,20),(30,30),(40,40),(50,50),(60,60),(70,70),(80\
                    ,80),(90,90),(100,100) ))
         ~        Dmnl
Average time for Error Correction= WITH LOOKUP (
         6*20/ Effect of PWR on Error Rates ,
                    ([(0,0) −(10,10)],(0,0),(10,10) ))
         ~        Minute
Available Cognition Resource= INTEG (
         (−Cognition Resource Allocation−Cognition Resource Allocating to Avoid Errors ),
                    1−Cognitive Load−Cognition for Error Detection and Recovery )
         ~        Cognition
Decrease of Mutual Understanding=
         MU* Effect of Innovations on MU/MUDAT
         ~        MU/ Minute
Cognition Resource Allocating to Avoid Errors=
         (" Desired Cognition for ED&R based on AER"−Cognition for Error Detection and Recovery\
                    )/COEAT
         ~        Cognition / Minute
Cognition for Error Detection and Recovery= INTEG (
         Cognition Resource Allocating to Avoid Errors ,
                    0.1)
         ~        Cognition
Cumulative Cognition Reduction by Innovation= INTEG (
         CCRA,
                    0)
         ~        Cognition
CCRA=
         Local Innovations and Changes * 0.005/CCRAT
         ~        Cognition / Minute
Errors Corrected=
         Perceived Mismatch Error Being Deleted / Mismatch Errors Perception and Deletion Average Time
         ~        Error / Minute
Change Rate of Pressure=
         ( Effect of Cognitive Load on CL Pressure −Cognitive Load Pressure )/CLSAT
         ~        Cognition / Minute
Errors from Mismatch 1= INTEG (
         ( Errors Generated−Mismatch Errors Perception Rate ),
                    0)
         ~        Error
Effect of Cognitive Load on CL Pressure= WITH LOOKUP (
         Cognitive Load −(Local Innovations and Changes * 0.005),
                    ([(0,0) −(1,1)],(0,0),(0.1,0.02),(0.2,0.055),(0.3,0.115),(0.4,0.21),(0.5,0.34),(0.6,\
                    0.5),(0.7,0.65),(0.8,0.82),(0.9,1),(1,1) ))
         ~        Cognition
Effect of Error Corrected on MU= WITH LOOKUP (
         MU,
                    ([(0,0) −(1,1)],(0,1),(0.1,0.715),(0.2,0.535),(0.3,0.41),(0.4,0.32),(0.5,0.25),(0.6,\
                    0.185),(0.7,0.13),(0.8,0.08),(0.9,0.035),(1,0) ))
         ~        1/ Error
Cognitive Load= INTEG (
         Cognition Resource Allocation ,
                    0.7)
         ~        Cognition
Cognitive Load Pressure= INTEG (
```

```
            Change Rate of Pressure ,
                0.65)
        ~       Cognition
Local Innovations and Changes= WITH LOOKUP (
        Cognitive Load Pressure ,
                ([(0.8,0)-(1,1)],(0.8,0),(0.82,0.24),(0.84,0.42),(0.86,0.555),(0.88,0.66),(0.9,0.745\
                ),(0.92,0.81),(0.94,0.87),(0.96,0.915),(0.98,0.955),(1,1) ))
        ~       Cognition
MU= INTEG (
        Increase of Mutual Understanding-Decrease of Mutual Understanding ,
                1)
        ~       MU
Mismatch Errors Perception Rate=
        Errors from Mismatch 1/Mismatch Errors Perception and Deletion Average Time
        ~       Error/Minute
Perceived Mismatch Error Being Deleted= INTEG (
        (Mismatch Errors Perception Rate-Errors Corrected),
                0)
        ~       Error
Effect of Innovations on MU= WITH LOOKUP (
        Local Innovations and Changes ,
                ([(0,0)-(2,0.5)],(0,0),(0.2,0.0175),(0.4,0.04),(0.6,0.0625),(0.8,0.095),(1,0.133),(\
                1.2,0.185),(1.4,0.24),(1.6,0.32),(1.8,0.407),(2,0.5) ))
        ~       Dmnl
Effect of Cognition on Work Rate= WITH LOOKUP (
        Cognitive Load ,
                ([(0,0)-(1,1.8)],(0,0),(0.1,0.19),(0.2,0.4),(0.3,0.6),(0.4,0.8),(0.5,1),(0.6,1.2),(\
                0.7,1.4),(0.8,1.6),(0.9,1.7),(1,1.8) ))
        ~       Dmnl
Increase of Mutual Understanding=
        (0.01+Errors Corrected*MU)*Effect of Error Corrected on MU*0.2
        ~       MU/Minute
MUDAT=3
        ~       Minute
COEAT=10
        ~       Minute
Average Error Rate= INTEG (
        AEAR,
                0.1)
        ~       Error
CAT=10
        ~       Minute
CCRAT=4
        ~       Minute
Errors From Mismatch=
        Errors from Mismatch 1+Perceived Mismatch Error Being Deleted
        ~       Error
CLSAT=5
        ~       Minute
Desired Work Rate=47
        ~       Task/Minute
"Effect of Cognition for ED&R on EDR"= WITH LOOKUP (
        Cognition for Error Detection and Recovery ,
                ([(0,0)-(0.3,1.5)],(0,0),(0.0333,0.15),(0.0667,0.44),(0.1,1),(0.133,1.24),(0.167,1.36\
                ),(0.2,1.43),(0.233,1.46),(0.267,1.49),(0.3,1.5) ))
        ~       Dmnl
Normal Amount of Computing Tasks= WITH LOOKUP (
        ManPower ,
                ([(0,0)-(100,100)],(0,0),(100,100) ))
        ~       Task/Minute
Effect of CL Pressure on Errors= WITH LOOKUP (
        Cognitive Load Pressure ,
```

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```
                ([(0,0)−(1,1.5)],(0,0.8),(0.1,0.802),(0.2,0.81),(0.3,0.818),(0.4,0.833),(0.5,0.87),\
                (0.6,0.95),(0.7,1.05),(0.8,1.19),(0.9,1.34),(1,1.5)  ))
        ˜       Dmnl
"Desired Cognition for ED&R based on AER"= WITH LOOKUP (
        Average Error Rate,
                ([(0,0)−(0.3,0.3)],(0,0),(0.05,0.051),(0.1,0.1),(0.15,0.15),(0.2,0.2),(0.25,0.25),(\
                0.3,0.3)  ))
        ˜       Cognition
Normal Work Rate=
        Normal Amount of Computing Tasks∗(1−Communication Overhead)
        ˜       Task/Minute
Normal EGR=
        0.1
        ˜       Error/Minute
********************************************************
        .Control
********************************************************˜
                Simulation Control Parameters

FINAL TIME  = 600
        ˜       Minute
        ˜       The final time for the simulation.
INITIAL TIME  = 0
        ˜       Minute
        ˜       The initial time for the simulation.
SAVEPER  =
        TIME STEP
        ˜       Minute [0,?]
        ˜       The frequency with which output is stored.
TIME STEP  = 0.125
        ˜       Minute [0,?]
        ˜       The time step for the simulation.
```

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Appendix E

List of Variables

Actual Work Rate

AEAR: Average Error Allocation Rate

AERAT: Average Error Rate Allocation Table

Available Cognition Resource

Average Error Rate

Average time for Error Correction

CAT: Cognitive Allocation Table

CCRA: Cognitive Change Rate Allocation

CCRAT: Cognitive Change Rate Allocation Table

Change Rate of Pressure

CLSAT: Cognitive Rate of Pressure Allocation Table

COEAT: Cognitive Error Allocation Table

Cognition for Error Detection and Recovery

Cognition Resource Allocating to Avoid Errors

Cognition Resource Allocation

Cognitive Load Pressure

Communication Overhead

Cumulative Cognition Reduction by Innovation

D Switch: Desired Work Rate Switch

Decrease of Mutual Understanding

Desired Cognition for ED&R based on AER: Desired Cognition for Error Detection and Error Rate based on Average Error Rate

Desired Work Rate

EDS Increase: Error Detection Skill Increase

Effect of Average Error Rate on AEAR: Effect of Average Error Rate on Average Error Allocation Rate

Effect of CL Pressure on Errors: Effect of Cognitive Load Pressure on Errors

Effect of CLP on Innovation: Effect of Cognitive Load Pressure on Innovation

Effect of Cognition for ED&R on EDR: Effect of Cognition for Error Detection and Error Rate on Error Detection Rate

Effect of Cognition for ED&R on Errors - Effect of Cognition for Error Detection and Error Rate on Errors

Effect of Cognition on Work Rate

Effect of Cognitive Load on CL Pressure: Effect of Cognitive Load on Cognitive Load Pressure

Effect of ECR and EC on AWR: Effect of Error Correction Rate and Error Correction on Average Work Rate

Effect of EDR on ECR: Effect of Error Detection Rate on Error Correction Rate

Effect of Error Corrected on MU: Effect of Error Corrected on Mutual Understanding

Effect of Innovation on Work Rate

Effect of Innovations on MU: Effect of Innovations on Mutual Understanding

Effect of KR on EDR: Effect of Knowledge Redundancy on Error Detection Rate

Effect of KR on MU: Effect of Knowledge Redundancy on Mutual Understanding

Effect of MU on Errors from Mismatch: Effect of Mutual Understanding on Errors from Mismatch

Effect of Performance Pressure on Cognitive Load

Effect of PWR and MU on EG: Effect of Potential Work Rate and Mutual Understanding on Error Generation

Effect of PWR on Error Rates: Effect of Potential Work Rate on Error Rates

Effect of Senior Junior Percentage on Error Rate

Effect of Senior Junior Percentage on Work Rate

Error Correction Rate

Error Detection Rate

Error Detection Skill

Error Detection Skill Increase Function

Error Detection Skill Normal Increase Rate

Error Generation Rate

Errors

Errors Corrected

Errors From Mismatch

Errors from Mismatch 1

Errors Generated

Increase of Mutual Understanding

Increased EDS per Corrected Error: Increased Error Detection Skill per Corrected Error

Innovation Knowledge Redundancy Function

Knowledge Redundancy

Local Innovations and Changes

Mismatch Errors Perception and Deletion Average Time

Mismatch Errors Perception Rate

MU: Mutual Understanding

MUDAT: Mutual Understanding Decrease Allocation Table

Normal Amount of Computing Tasks

Normal EDR: Normal Error Detection Rate

Normal EGR: Normal Error Generation Rate

Normal Work Rate

Perceived Mismatch Error Being Deleted

Perceived Performance Pressure

Perceived Stress Adjustment

Potential Work Rate

Pressure from Performance Gap

PSAT: Perceived Stress Adjustment Table

Required Effort for Each Computation

Senior and Junior Team Members

Shared MU Adjustment: Shared Mutual Understanding Adjustment

Task Deduction Ratio

Task Stress Function

Total ManPower