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Dynamics of Performance and Cognitive Human Factors in a Manufacturing System

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1. Introduction

Human error is a generic term that englobes situations in which the objectives of mental or physical activities are not met and the source of the previous cannot be attributed to chance (Reason, 1990: 9). The problem of human error can be viewed in two ways: the person approach related to faults and violations of procedures produced by the employee's inattention, poor motivation, forgetfulness, etc. and the system approach which focuses on the work conditions as the factor leading to errors (Reason, 2000). The EU-OSHA Multi-annual strategic Programme 2014-2020 states that characteristics of job settings that produce negative consequences for the employee or the organization, such as weekend or night shifts are declining. However, other negative patterns still exist such as jobs with poor learning opportunities or poor training, shift work or non-fixed working schedules, higher work intensity and health-related absenteeism. Since the human operator is the center of manufacturing processes (Layer, Karwowski, & Furr, 2009), improving these processes necessarily calls for attention to human factors.

According to Zaeh, Wiesbeck, Stork, and Schubö (2009) in order to predict workers' task performance, it is essential to understand the cognitive processes needed for performing such activities. Manual processing activities are those in which no machines are used and the operator interacts directly with the materials. These activities demand mental processing capacities such as perception, response selection and action execution. Understanding cognitive processes is necessary since individuals' mental resources are limited and an adequate distribution of them to relevant task aspects is necessary. However, understanding cognitive processes is not sufficient, factors associated with the work environment also play an important role. The interaction of environmental and cognitive factors can affect human abilities and concentration influencing the quality of the work performed (Hamrol, Kowalik, & Kujawińsk, 2011).

Local, regional and global safety and health frameworks recognize both the potential negative effect that work has on workers and how this can affect the enterprise (Burton, 2010; EC, 2014; MSAE, 2013). In the European Union, 27% of the workers (56 million workers) are exposed to factors that disturb mental well-being in the workplace causing production impairments and costs to enterprises (EU-OSHA, 2013). Nevertheless, the great majority of enterprises only address health and safety protection to fulfill legal obligations (González, Cockburn, & Irastorza, 2010). Highlighting the performance-related benefits of improving health and safety systems in enterprises can act as a motivator for raising awareness and increasing commitment from managers regarding the well-being of workers.

Human-made systems are difficult to study, analyze and predict because of their complexity and dynamic and stochastic behavior. Simulation appears to be the appropriate technique for modeling and analyzing advanced manufacturing systems (Banks et al., 1996; Hlupic and Paul, 1999; Reeb and Leavengood, 2003; Robinson, 2004). Nevertheless, "*How to make such models quantifiable and computable is an open research problem*" (Morries, Ross, & Ulieru, 2010). According to Baines (2007) the interaction and mediating effects of organizational variables needs to be captured in human performance modeling. Some modeling efforts have already been done using methodologies such as Discrete Event Modeling (DES) or Dynamic Bayesian Networks. Nevertheless, Human Performance modeling using System Dynamics (SD) can benefit from the fact that in these models, feedback plays a significant role in the calculation of the parameters' values over time (Urbanic & Bacioiu, 2013). A second advantage is the transparency provided by the use of this modeling technique. The use of

System Dynamics would them facilitate the identification of the relationships between variables and key levers of the system, which is key for determining actions to take.

Some work has already been done in System Dynamics regarding human factors. (Qian, Labaka, Lango, & Gonzalez, 2005) modeled cognitive load in an emergency room focusing on cognitive load as a function of the amount of work; Block and Pickl (2014) focused on the AMO theory (Performance of an individual determined by its ability, motivation and opportunity); (Sawicka, 2008) modeled cognitive load in a learning environment; Xinyuan (2006) modeled human performance in a power plant merging workload, physical load and cognitive load together in a variable called stress. Nevertheless, as mentioned already in a manufacturing task setting, human performance impairments can be caused by an excessive amount of work but also by factors related to the task itself or such as complexity, time-on-task, attention required, etc. These factors were not found in any of the previously mentioned models.

This work intends to confirm whether a generic System Dynamics model incorporating human cognitive factors in a manufacturing process can be used for prediction in order to help managers with the optimization of their task designs to ensure worker well-being and the productivity of the organization. The first issue addressed was how could human cognitive factors be represented in a System Dynamics model and which already quantified models could be used for this representation. The second issue was whether a generic model could be useful to predict performance in any setting. The results showed that a generic model cannot be created for prediction using only theoretical research, empirical research is necessary, as the topic is complex, including many uncertainties and conflicting theories. Nevertheless, the use of the model for creating awareness of the underlying processes of the relationships between cognitive human factors and performance is highlighted and a contribution is made by the translation of already quantified mathematical models into System Dynamics and by a proposal for the operationalization of a theoretical model for representing a sector of the model. **The nature of the job** as its name indicates varies with activity to activity, human cognitive factors are affected differently in diverse settings.

In the following paragraphs, the construction of the System Dynamics model of Cognitive Human Factors is described. First, a literature review is performed in order to provide a general understanding of the topic and existing theories. Second, an already quantified empirically tested model will be selected, this model will be used as the basis for the System Dynamics Model. Third, both the process undertaken for the model construction and the dynamics of the final model are explained. Fourth, model validation is performed and finally, policy recommendations are suggested.

1.1 Research Objective

The objective of this study is to contribute to the existing work on human cognitive factors by increasing the pool of knowledge and understanding of their interaction and their effect on individuals' performance within a manufacturing setting. The previous will be done with the creation of a System Dynamics model and its prediction capabilities will be assessed. This model is also expected to be used as a boundary object in order to increase awareness of managers on the topic in order to encourage the use of better policies for creating healthier and more productive organizations and employees within the organization.

First, model characteristics of occupational health and safety frameworks will be identified. Second, this identification will be used as an input for selecting an existing quantified model involving cognitive factors. Third, the selected model will be translated into system dynamics and combined with a model of an integrated workflow process to represent the effects that cognitive factors can have on workers' performance and affect the overall productivity. Third, a dashboard showing effects of changes to the system on important policy variables will be generated for the purpose of generating awareness on managers of how cognitive factors can affect a manufacturing system and how to overcome/avoid negative effects produced by them.

1.2 Research Questions

The research evidence to date suggests that human factors are important when it comes to performance in manufacturing processes. Bearing this in mind, this theory-oriented research will investigate how to represent in a quantified System Dynamics model the effects that cognitive factors have in the performance of a manufacturing task and whether this representation could be used for prediction. This work intends to provide an answer to the following questions.

1. What are that task characteristics/design elements in a manufacturing task and their relationship with human cognitive factors?
2. Which evidence-based human performance/safety and health models are relevant to characterize the effects of task characteristics/ design on cognitive factors?
3. What is the effect that human cognitive factors can have on performance?
4. What policies would ensure that productivity is maximized?

2. Theoretical Background

> *"Remarkably, given that fatigue has been studied formally for well over 100 years, there is still no scientifically mature theory of its origins and functions" (Hockey, 2011).*

A general definition of a manufacturing process is "*the process of making wares by hand or by machinery especially when carried on systematically with division of labor*" (Merriam-Webster, 2015). Where the term *wares* is used to denote products, "something made from raw materials by hand or by machinery" (Merriam-Webster, 2015). Even from these simple definitions, the complexity of a manufacturing process can be inferred by the interaction of three different kinds of resources: materials, machinery, and human labor. Allwood, Childs, Clare, De Silva, Dhokia, Hutchings et al. (2016) analyzed factors that can act as bottlenecks in a manufacturing process and categorized them in three classes: **Process limits** (materials), **system limits** (people with constrained capacities) and **co-ordination limits** (management of process and system). The authors indicated that a relationship exists between the three bottlenecks and improvement in one area may only reveal a bottleneck in another one. Normally attention is paid to materials and machinery but the human factor is commonly ignored. Layer et al. (2009) also highlighted this point, putting special emphasis on the limits introduced by the cognitive capacities of the operator. They stated that manufacturing systems have demands for more flexible, adaptable, efficient systems and improving them necessarily requires a focus on operators.

A simple representation of the interrelationships between the worker and the organization was given by Genaidy's work compatibility model. This model focuses on improving the worker's well-being and as a consequence improving the well-being of the whole organization. It aims at measuring the compatibility between the workforce and the work environment. (Genaidy, Karwowski, Salem, Jarrell, Paez, & Tuncel, 2007). The individual well-being in the model is relevant, as it not only leads to health outcomes for the individual but it also improves the organizational well-being. Enterprises must account for human factors in order to ensure the well-being of the organization.

2.1 Performance Shaping Factors

Focusing on the operator necessarily implies an analysis of the factors within a working environment that can affect the worker's and the organization's performance. Existing frameworks use different representations of these factors. The regulatory framework for workplace health and safety in Great Britain (Health and Safety Executive) created an integrated model of human factors for facilitating the explanation and communication of the need for optimization of the relationship between demands and capacity for human a system performance (Bellamy & Geyer, 2007; Genaidy et al., 2007). Several literature sources were used related to error, performance shaping factors, physiology, anthropometry, individual and organizational stress, ergonomics, information processing models, human performance and the content of academic programs to arrive to the following taxonomy: (1) **performance shaping factors (PSFs) affecting demands,** concerning both the *nature of the job* (Degree of monotony, Variety, etc.) and *task design* (displays and controls, operator information, workplace layout, workload, written procedures); (2) **environmental PSFs**, concerning *elements from the environment* such as heat, lighting, noise and *stressors* such as false alarms or process upsets; (3) **capacity PSFs** *relating to individuals* (e.g. experience, competence, attitudes, risk perception), *psychological capacities* (e.g. attention, alertness, vigilance, arousal; perception and adaptation; cognition and understanding; memory) and *anatomical and physiological capacities* (work rate, biomechanical and anthropometric capacities); (4) **human behavior outcomes,** which are symptoms of demand capacity mismatch (e.g. absenteeism, fatigue, illnesses, injury, human errors (slips and mistakes) and violations). Work demands, elements from the environment, individual's capacity and human behavior outcomes act simultaneously to shape the results of the organization (performance).

PSF affecting demands		Capacity PSF	
Categories	Examples	Categories	Examples
Task design	Displays and controls Information provided Workplace layout Workload Written procedures	Related to Individuals	Experience Competence Attitudes Risk Perception
		Psychological capacities	Attention, alertness, vigilance Perception and adaptation Cognition and understanding Memory
Nature of job (Task Characteristics)	Degree of monotony Variety Complexity Isolation Repetitivity Risk	Anatomical/ physiological capacities	Body Measurements Biomechanical capacities Antropometric capacities

Human Behavior Outcomes		Environmental PSF and stressors	
Examples (no categories)		Examples (no categories)	
Absenteeism	Injury	Heath	False alarms
Fatigue	Human Errors	Lighting	Process upsets
Ilnesses	Violations	Noise	

Table 1. HSE Performance Shaping Factors

2.2 Cognitive Factors

Neumann and Dul (2010) performed a systematic review of studies regarding human and operation system effects in manufacturing settings. One of their conclusions was that most of the studies focus on physical workload and more research must be done on psychosocial aspects. This is reinforced by the fact that modern technology in many working environments imposes greater cognitive demands upon operators in comparison with physical demands (Singleton, 1989). In line with these findings, the focus of this work will be on cognitive human factors. Understanding the cognitive processes involved in manual assembly is essential for predicting the worker's task performance. Mental resources of humans are limited and have to be distributed and allocated to relevant task aspects. Zaeh et al. (2009) defined **Cognitive Factors** as features from work-related activities that required the use of cognition: **attention** (alertness, selective and sustained attention), **working memory** and **executive function** (initiative, decision-making, problem-solving). The ISO 10075 identified **mental fatigue, monotony, reduced vigilance, and mental satiation** as terms related to **mental workload** (ISO, 1991). Nevertheless, a precise definition of cognitive factors or psychological capacities (attention, alertness, vigilance, fatigue, working memory, etc.) is elusive (Mélan & Cascino, 2014).

Not only definitions are elusive but also how the effects of psychological capacities manifest themselves. According to (Cummings, Gao, & Thornburg, 2016) *cognitive fatigue* influences performance by creating slow responsiveness and reduced task performance, while vigilance would lead to a delayed response, missed signals and increased false alarms. Nevertheless, a differentiation from these effects could pose difficulties, the previous paragraph serves as an example of this, a "Delayed Response" could be interpreted as the same as "Slow responsiveness".

2.3 Theories of Cognitive Factors and Performance

In the following paragraphs, an overview of the principal theories involving human cognitive factors and their effect on performance will be presented. The theories cover the performance shaping factors affecting demands, capacity performance shaping factors (except for anatomical and physiological capacities as they concern human physical factors) (see Table 1. HSE Performance Shaping FactorsTable 1.). As its name indicates, Performance Shaping Factors are the determinants of performance of individuals. For modeling purposes, it is necessary to identify how demands on the operators (PSF affecting demands) and their capacity (Capacity PSF) can generate performance impairments. The theories give different explanations for the previous. At the end of the review, two models will be described which merge previously existing theories.

Cognitive load theory states that working memory is divided into three load categories: intrinsic load, germane load and extraneous load. This theory describes the interaction between these loads. Intrinsic cognitive load is the amount of working memory required to assimilate simultaneously the number of elements imposed by the task. Extraneous load is the amount of working memory needed to assimilate information due to factors of the external environment (displays, time pressure, noise, etc.). The germane load is the amount of working memory required to consciously process, construct and automate schemas. In a manufacturing process, it would be the load generated by restructuring problem representations to solve tasks easier (Galy, Cariou, & Mélan, 2012). Mélan and Cascino (2014) applied cognitive load theory to real job situations by associating intrinsic load with high task difficulty and extraneous load with high time pressure. These loads have an effect on working memory and on mental efficiency. The authors suggested that germane cognitive load is determined by both the remaining resources after covering intrinsic and extraneous load needs and by the individual's functional state (alertness). Germane load allows individuals to elaborate efficient strategies. Individuals engaged in a task with characteristics such as high difficulty and time pressure will show performance detriments due to a low availability of resources for creating efficient strategies. These performance detriments will vary during the day as alertness and task performance do not have a linear relation and the impact depends on factors such as time of the day. This view corresponds to the cognitive psychology view; in contrast, an occupational psychology perspective would deal with the individual's perception of work demands affected by different factors of the work environment. This view is represented by two models, Karasek's **Demand-control support Model**, which states that performance depends on the individual's perception of their work environment (task demands, control possibilities and social support); and the **Effort-Reward-Imbalance model**, which specifies that safety and performance depend on job-related psychological effort, reward and the level of commitment of employees.

The **Yerkes-Dodson principle** has been called as the "law of performance" and states that a nonlinear relationship exists between arousal and performance. This relationship is characterized as an inverted U. This characterization comes from the notion that moderate levels of arousal lead to optimal performance, while low/high levels of arousal would lead to decreased performance (Staal & Server, 2013). This principle also states that the optimal performance point varies according to task difficulty and will be different for each person. The major criticism towards this principle has been in regards to the omission it makes on addressing psychological factors (individuals react differently to the demands imposed on them) (Pomeroy, 2013). The **Yerkes-Dodson principle** has been commonly used and extended. Cox and McKay (1976) presented a human performance curve that differs from the **Yerkes-Dodson principle** in the fact that in their model it is not arousal what determines performance but rather the perceptions that individuals have of the demands imposed on them. The model linked stress to performance by categorizing individuals' perceptions of demands in four different states: boredom, eustress, distress and exhaustion and portraying them in an inverted U shape as the **Yerkes-Dobson principle**. Boredom would happen when low demands are percieved and it would result in low performance, eustress would lead to optimum performance as the individual presents moderate arousal with moderate demands, distress leads to low performance as the individual would be in a high arousal state and under high demands. Exhaustion would be the opposite state in comparison with boredom as it would arise when the demands are the highest and performance is the lowest.

Limited-resources theories state that high cognitive workload implies high-performance impairments as individuals have limited information processing resources. Two different views account for the origin of these impairments. Kahneman (1973)'s work introduced the **Central-Capacity Model of Attention** which supposes the existence of a single resource pool, with a maximum capacity, from where attentional resources are taken and allocated according to task demand. Whenever a high demand for resources exists the pool gets depleted and performance gets impaired. Wickens (2008) work provides a **Multiple Resource View** based on Kahneman's work but instead of assuming the existence of a central pool, it considers a pool divided into four categories: stage of processing (perception cognition or response), sensory modality (visual, auditory, etc.), code processing (spatial or symbolic) and vision (Focal versus ambient). Performance impairments happen when more than two or more tasks are intended to be performed at the same time with demanding resources of the same pool.

Underload theories and **overload theories** account for the effects of sustained attention (performing tasks that require sustaining focus of attention over long time durations) on performance. **Underload theories** (also called mindlessness hypothesis) state that time causes attention to shift from the external environment onto task-unrelated thought (mind wandering) on monotonous and under-stimulating tasks, causing a decreased ability for detecting critical events. **Overload theories** follow the **resource-depletion hypothesis** stating that humans possess limited information-processing resources, a vigilance decrement comes from the depletion of information processing resources (Thomson, Besner, & Smilek, 2015).

Some theories also associate performance impairments caused by sustained attention tasks with a lack of stimulation and fatigue. **Arousal theory** indicates that lack of stimulation generates decrements of performance in tasks requiring sustained attention. The previous happens because ~~due to stimulation~~stimulation allows alertness ~~can~~to be maintained at a required level. Nevertheless, Smit, Eling, and Coenen (2003) indicate that a limitation of **arousal theory** is the lack of recognition of the fact that tasks can also be mentally demanding. The authors tested the resource theory of vigilance and concluded that performance impairment arises because mentally demanding tasks need a great deal of resources that can cause alertness to drop, so they consider resource demands rather than task duration as the determinants of vigilance performance. **Habituation theory** is similar to **arousal theory**. It states that monotonous, repetitive stimulations create a decrease of arousal which leads to an impaired ability to detect critical signs and a vigilance decrement (Larue, Rakotonirainy, & Pettitt, 2010). Nevertheless, they also highlight that this process differs from fatigue, due to the fact that change in stimulation can improve the impaired performance but in the presence of fatigue, performance wouldn't be improved as rest would be necessary to show these results. This differentiation is relevant because addressing the lack of stimulation in tasks would not completely avoid performance impairments as *cognitive fatigue* would still be in play.

2.3.1 Merged Theories

Thomson et al. (2015) proposed the **Resource-Control Theory of Mind Wandering** accounting for elements of both overload theories and underload theories. The central points of this theory are: (1) the amount of attentional resources is fixed and can't change over time; (2) Mind wandering would consume part of the resources available for the task; (3) The default state of individuals is mind wandering, executive control is needed to prevent attention switching from the task to this state; (4) The more time a worker spends on a task, the less executive control he can excise; (5) Finally, mind wandering is not always detrimental to performance as many tasks require less than the overall resources available.

Langner and Eickhoff (2013) provide a similar framework regarding attention and performance. They suggest that performance impairments happen due to an unbalance between benefits (rewards from activities) and costs (attention demands), which shifts individuals focus on the goal (completing the task). Maintaining attention in non-rewarding activities for the individual with high attention demands requires constant self-regulation. As time-on-task increases, self-regulation capabilities referred to executive control in the **Resource-Control Theory of Mind Wandering**, decrease. The consequences of the previous are the following: First, mental fatigue or resource depletion happens, meaning that the individual will have lower resources to process task-relevant information; Second, self-regulation would diminish (less goal maintenance) guiding the individual to a mind-wandering state. In comparison with the **Resource-Control Theory of Mind Wandering,** the authors also consider motivational elements. An imbalance between perceived costs and benefits of maintaining performance over time results in a reduction of effort exerted in the task. The amount of effort exerted would depend on the individual's motivation. The authors are more flexible on defining the causes for this behavior and state that it could be either in line with the resource-depletion view or with underload theories. They also consider performance impairments to be due to the combination of elements in both theories (resource depletion or lack of self-regulation). Finally, arousal is considered to decrease with the predictability of the task at hand and extra effort is needed for compensation. "Simple, repetitive tasks requiring continuous attention were often found to be associated with increased stress responses and higher subjective effort expenditure, compared with more complex,

variable tasks" (Langner & Eickhoff, 2013).

	Theory	Main concepts covered
1	**Cognitive Load Theory**	Working memory divided into three loads: intrinsic, extraneous, germane. Task difficulty, time pressure, alertness
2	**Demand-control-support Theory**	Task demands, Executive control, social support
3	**Effort-Reward-Imbalance Theory**	Task variety, psychological effort, reward
4	**Yerkes-Dobson principle**	Arousal
5	**Cox and McKay (1976)**	Task demands, boredom, stress, distress, exhaustion
6	**Limited-Resources Theories**	Attentional resources, task demands
7	**Arousal Theory**	Commitment, alertness, lack of stimulation, sustained attention
8	**Habituation Theory**	Resource depletion, fatigue, vigilance, stimulation
9	**Underload Theory**	Sustained attention, task-unrelated thought, stimulation
10	**Overload Theories**	Resource depletion, vigilance
11	**Resource-Control Theory of Mind Wandering**	Limited processing resources, attention, executive control, subjective effort, task-unrelated thought (mind wandering)
12	**Langner and Eickhoff (2013)**	Attention demands, self-regulation, time-on-task, mental fatigue, motivation, resource depletion, goal maintenance

Table 2. Overview of theories reviewed

2.4 Mathematical model selection

An extensive literature review was performed for the selection of the mathematical model for the construction of the System Dynamics model. A challenge was encountered when performing this search as many of the existing models don't include the necessary detail for creating the System Dynamics formulations. They focus on learning rather than in an occupational setting or are designed to predict performance in a response task. A response task is a task in which people must respond to stimuli presented in an infrequent and unpredictable form(Peebles & Bothell, 2004). As previously mentioned, cognitive factors will be represented by cognitive/mental workload. To increase the possibilities of finding a quantified model also mental workload's related terms were included in the search (attention, vigilance, *cognitive fatigue* and boredom).

The search lead to nine models which were rated according to the input variables, output variables, System Dynamics compatibility, relationship with human cognitive factors and modeling time requirements vs. time available. The **fatigue index** was the model with the highest score, as the input requirements consisted of information easy to access for managers and besides considering homeostatic and circadian elements, task related characteristics were also included. Many of the models included individual factors, which make the results more accurate but also increase the complexity and data requirements for its use.

#	Model	Name	Reference	Description	Rating
1	Attention	Real-time performance modelling of a Sustained Attention to Response Task. GLMMs	(Larue, Rakotonirainy, Pettitt, 2010)	Model and detection of vigilance decline in real time through participants' reaction times during a monotonous task	2
2	Attention	Real-time performance modelling of a Sustained Attention to Response Task. Dynamic Bayessian Networks and Neural	(Larue, Rakotonirainy, Pettitt, 2010)	Model and detection of vigilance decline in real time through participants' reaction times during a monotonous task	2
3	Attention	Model of attention and situation awareness (A-SA).	(Wickens, McCarley et al. 2003)	Includes two components: a perception/ attention module and a cognitive Situation awareness module. Situation awareness affects performance as it determines the likelihood of correct behavior.	2,5
4	Attention/Fatigue	SAFTE-FAST	(Hursh & Eddy, 2005)	(1) circadian rhythm; (2) cognitive performance recovery and decay rates (sleep/awake) ; and (3) sleep inertia	2
5	Boredom	Modelling human boredom at work	(Azizi, Zolfaghari et al. 2010)	Bayesian Networks. mathematical formulations and a probabilistic framework	2,67
6	Fatigue	FAID	(Roach, Fletcher et al. 2004)	Fatigue is modeled as a simple input-output model of hours-of-work that are affected by cicardian, recovery and recency-of-work-factors.	1,75
7	Fatigue	The three-process model of alertness and its extension to performance, sleep latency, and sleep length	(Åkerstedt and Folkard 1997)	Predicts alertness/performance. Contains a circadian and a homeostatic component. Identifies levels for risk of performance/alertness impairment starts and predicts sleep latency.	2
8	Fatigue	Circadian Alertness Simulator (CAS)	(Moore-Ede, Heitmann et al. 2004)	Designed for fatigue risk assessment in transportation. Estimates fatigue risk of an individual's sleep-wake-work pattern in combination with individual-specific settings	1,5
9	Fatigue	Fatigue Risk Index (FRI)	(Spencer, Robertson et al. 2006)	Designed for comparisson of work schedules, examines the potential impact of changes to features of work schedules.	2,75

Figure 1. Model selection

2.4 Conclusion

Many theories account for cognitive factors and their influence on performance but there is still no agreement on how this influence occurs. A common element considered in most theories is resource depletion. Nevertheless, whether this depletion is caused by mind-wandering, executive control, task demands, lack of stimulation, time-on-task, effort or a combination of the previous, hasn't been exactly agreed upon. Many of the factors included in the theories are interrelated and would require the use of soft variables (attributes of human behavior for which numerical data is often unavailable or non-existent) for modeling purposes and include non-linear characteristics. This System Dynamics model will serve as a synthesis of some of the previous views/models and will allow a further understanding of how cognitive factors affect performance.

3. Methodology and Research Strategy

The aim of this section is to give a description of the methodology and research strategy followed for the creation of this work. This research used a qualitative approach to explore the effect that cognitive human factors have in the productivity of a manufacturing process. The research was done in close collaboration with the Netherlands Organization for Applied Research (TNO). Existing quantified empirical models of cognitive human factors were merged into a System Dynamics model.

The information was obtained from various sources: First, in the conceptualization stage (Problem definition and system conceptualization) a literature review was used for analysis of quantified empirical models, they were compared with the aim of selecting the models to be included in the SD model. Second, the initial structure of the System Dynamics model representing a generic manufacturing process was created. The selected models were integrated into the manufacturing process structure, using the information gathered from existing quantified models and information from theoretical models was used as a complement. "*SD models frequently include "soft" variables, which may be difficult to empirically quantify. Identifying the system's structure is paramount, even if some components of the model rely on anecdotal data and the best estimates of subject matter experts*" (Sweetser, 1999). Third, after the model had been formulated, testing was done. This stage comprises structure verification of the model which according to Luna-Reyes and Andersen (2003) may involve comparing model assumptions to relevant literature, first conducted on the basis of the model builder's personal knowledge and it can then include an assessment by others with direct experience from the real system. All variables and relations were derived from and checked against literature. Information from an existing industrial case provided by TNO concerning order picking in the Vanderlande Industries was used for both calibrating the model and for verification. According to Andersen, Luna-Reyes, Diker, Black, Rich, and Andersen (2012) dis-confirmatory interviews can be used to increase user confidence in structure and behavior of the model because they pinpoint biases introduced in the coding process, they support efforts to improve the structure of the model and can help the customer focus on what should be done and implementation steps. For this purpose, a Group Model Building (GMB) session was conducted in which the model was presented to experts.

After performing structure and behavior tests for validation of the selected model, it was concluded that it could not replicate the behavior showed by the case study. However, a model extension was then performed and two sectors were added (**effort sector** and **learning curve sector**). The models used for the extension were selected with the purpose of correcting the trend showed in the results of the model. This selection was made based on the literature review already performed and using input from the first Group Model Building session. The information, for both building the structure and for the parameters was obtained from the literature.

As previously mentioned, two sessions of Group Model Building were included for the development of this work with the objective of eliciting model structure, performing validation and engaging the final user of the model (TNO) in the process of model construction. Group model building is a form of participatory modeling that aims to deeply involve stakeholders (clients) in the process of model construction (Vennix, 1999). The purpose of Group Model Building is to elicit model structure and to engage stakeholders (client teams) in the process of model construction, analysis and decision making (Andersen, Vennix, Richardson, & Rouwette, 2007). The purpose of the sessions was to review the structure and for the partner organization (TNO) to get acquainted with the System

Dynamics methodology and with the model. The participants in both sessions were experts in human factors from TNO. The first Group Model Building session was done considering only the **cognitive fatigue sector**. The second Group Model Building session concerned the whole system and was performed using the management flight simulator developed in this work. These sessions were useful in order to verify the structure of the system, obtain input for the extension of the model and the dynamics involved and for familiarization of the partner organization with the model.

The final stage of System Dynamics model construction is the implementation stage. This stage normally comprises policy analysis and use. In this case, the objective is not to solve a specific problem but to create a tool to show different scenarios of how human factors affect a manufacturing process. No implementation of the scenarios need to be assessed but rather the transference of knowledge of the model to TNO needs to be ensured. For this purpose, a participatory modeling session will be included. "Group techniques generate discussion among actors about the meaning of both the results of the policy experiments and the stories generated by the model" (Luna-Reyes & Andersen, 2003).

System Dynamics modeling is the methodology used in this work to represent how cognitive human factors interact and affect performance within a manufacturing system. System Dynamics stands out by its ability to represent both social and physical systems, as it can easily portray the nonlinearities, feedback loop structure and complexity embedded in them (Forrester, 1994). System Dynamics was developed during the 1950's by Jay W. Forrester and mixes ideas from control engineering (feedback and system self-regulation), cybernetics (role of information in control systems) and principles of human decision-making from the field of organizational theory. This method deals with the dynamics of complex systems, that is the behavioral patterns generated by the system over time (Meadows, 1980).

According to Meadows (1980), the basic assumptions of this methodology come down to a causal structure, feedback loops, delays and nonlinearities. A causal structure implies that explanations of problems within its internal structure. System Dynamics models are made up of several feedback loops integrated together. Most variables are determined endogenously and few external influences are included, these external influences refer to variables that would modify the system but they would not be influenced back by the system. A reinforcing loop (positive) tends to amplify disturbances and create growth while a balancing loop (negative) has the opposite effect and guides the system towards a specific goal or equilibrium point. Material and information delays are considered, they affect the behavior of the system and can be the source of an oscillatory behavior. Nonlinearities cause loops to vary in strength depending on the particular state of the system. Finally, it is important to highlight that the model behavior is created by the combination of the previous elements. In order to represent them, levels and rates are used. A level is an accumulation of material or information and a rate represents decisions, actions of changes to or from the level.

According to Luna-Reyes and Andersen (2003), System Dynamics models are normally built for supporting decision-making by providing a general understanding of the system. The authors highlight that these models are small, aggregated and simple. They are usually derived from mental models making them intuitive and understandable and a requirement for these models is that they should represent a real-world structure. Parameter estimation is not highly relevant as these models are oriented to provide a general understanding of the system by its behavioral characteristics and nonlinearities makes the system less sensible to exact parameter values. The process for constructing a System Dynamics model is iterative as the modeler intends to test a dynamic hypothesis of the causal structure that generates the behavior of a specific system over time. The software that will be used to model the system is Vensim for creating the model, and it will be used in conjunction with Forio for creating the flight simulator.

System Dynamics was the methodology chosen to represent human cognitive factors as it allows the inclusion of non-linear relationships and causalities. Human-made systems are difficult to study, analyze and predict because of complexity and dynamic and stochastic behavior they present, simulation appears to be the appropriate technique for modeling and analyzing advanced manufacturing systems (Banks et al., 1996; Hlupic and Paul, 1999; Reeb and Leavengood, 2003; Robinson, 2004). According to (Baines, 2007) interaction and mediating effects of organizational variables is a key characteristic needed in human performance modeling. Human performance modeling using System Dynamics (SD) can benefit from the fact that feedback plays a significant role in values of the model's parameters over time and these models are easier to follow (Urbanic & Bacioiu, 2013). The major advantage of the previous is the fact that using System Dynamics modeling the relationships between variables and key levers of the system can be easily identified. This identification facilitates the determination of plausible actions to take.

4. Model Construction

The purpose of this section is to describe the process followed in order to achieve the construction of the System Dynamics model. A brief overview of the problem will be given, followed by the dynamic hypothesis. The dynamic hypothesis was defined by Albin, Forrester, and Breierova (2001) as "*diagrams illustrating the basic mechanisms driving the system's dynamic behavior*". According to the authors, its purpose is to identify and test the consequences of the feedback loops. Finally, at the end of this section, the sectors that compose the model will be described.

It is important to highlight that the terms *cognitive workload* and *mental workload* are used interchangeably. The terms *cognitive fatigue* and *mental fatigue* are also used interchangeably. The reason for the previous is that both terms are used in theories and models listed in the literature review. The terms used by the authors were conserved. Finally, to refer to workers the terms individuals or operators were used. The words workers and individuals were used when talking in general terms and operators was used to refer to the people involved in the case study. Throughout the text, several words will be presented in italics. The previous was done to facilitate the understanding of the text. These words represent variables included in the model.

4.1 Problem Definition

Human cognitive factors can affect the productivity of individuals within a manufacturing setting. Manual processing activities are those in which no machines are used and the operator interacts directly with the materials. These activities demand mental processing capacities such as perception, response selection and action execution. Understanding cognitive processes is necessary since individuals' mental resources are limited and an adequate distribution of them to relevant task aspects is necessary. *Cognitive fatigue* in individuals influences productivity by creating slow responsiveness and reduced task performance (Cummings et al., 2016).

4.1.2 General overview of the system

The **characteristics of a task** define the *productivity* of individuals involved in the production within a manufacturing system. The managerial focus is always to increase *productivity* in order to obtain more revenues. They perform the **task design** according to the goals of the organization. Nevertheless, this **task design** can have a counterintuitive behavior and instead of increasing *productivity,* it could cause decrements. As certain task characteristics and **task design** also affect **human cognitive factors** and *productivity* can be impacted.

Manufacturing Task Characteristics – Characteristics of manufacturing tasks that cannot be manipulated by managers such as complexity, variability, attention required.

Manufacturing Task Design - Characteristics of manufacturing tasks that can be manipulated by managers such as time-on-task, breaks, work schedules, deadlines, production goals.

Cognitive Human Factors – factors involved in activities that require the use of cognition: attention (alertness, selective and sustained attention), working memory and executive function (initiative, decision making, problem solving). (Valdez, Reilly, & Waterhouse, 2008). The term human cognitive capacities is also used to refer to cognitive human factors in order to facilitate understanding.

Performance measures (Human Behavior Outcomes)- means of quantifying the efficiency and effectiveness of manufacturing tasks (e.g. error rate, absenteeism rate, accident rate, production rate).

Productivity- items processed by the worker by period of time.

A manufacturing task has features that can be controlled by managers (**task design**) and characteristics of the task itself (**task characteristics**) and cannot be modified. Both of these factors define the productivity of workers in manufacturing settings. The task design refers to those factors that managers can control and modify. According to the company's goals, managers take decisions that determine the **task design**. For example, productivity might depend on a) task complexity (task characteristic) and b) the amount of time assigned to the task (task design). A less complex task will generate better results (higher productivity) in the same amount of time, as compared to a more complex task. Managers can decide how many hours, workers would be assigned to those tasks. However, human cognitive factors also play an important role, both task characteristics and task design can cause human behavior outcomes (fatigue, errors) which would affect the overall performance (productivity). For example, if a worker is performing a complex task during a prolonged time his level of attention might diminish causing more errors and in turn diminishing productivity. Managers take decisions comparing the actual state of the company with the desired conditions aiming to achieve productivity goals, affecting the task design. An improper task design (not considering human cognitive factors) can lead to performance impairment rather than getting the company closer to the desired conditions.

4.1.3 Reference Mode

The reference mode used at the beginning for the construction of the model is represented by Figure 2. It is based on descriptions found in literature, as no information from the case study was available at the time when the construction of the model was started. It follows the assumption that over time *cognitive fatigue* reduces performance (Langner, Steinborn, Chatterjee, Sturm, & Willmes, 2010).

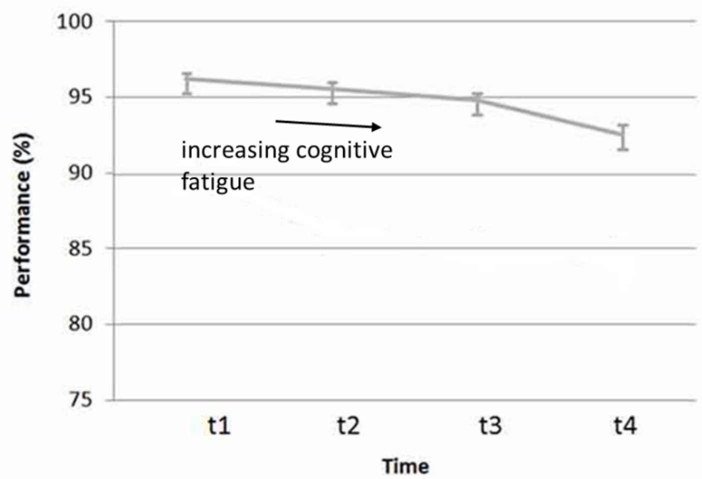

Figure 2. Reference mode

Source: Adapted from (Borragán, Slama, Destrebecqz, & Peigneux, 2016)

4.2 Dynamic Hypothesis

As previously mentioned the dynamic hypothesis aims to identify the underlying mechanisms that lead to the behavior observed. In this case, it aims to explain the fact that productivity decreases over time as *cognitive fatigue* increases.

4.2.1 Initial hypothesis

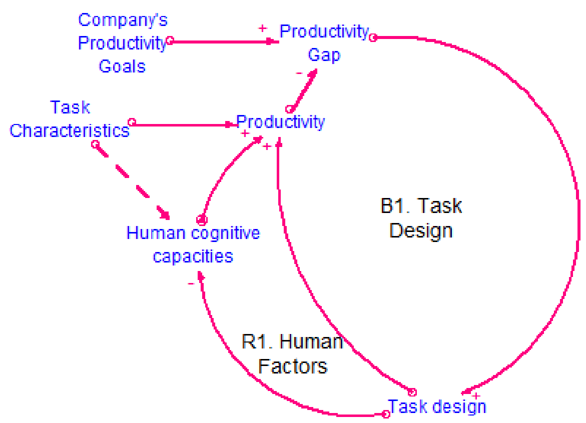

Figure 3. Initial Dynamic Hypothesis

The initial hypothesis consists of the following: **task design** (e.g. long working hours, time constraints) is made by managers in order to reach the company's goal by comparing the current status (*productivity*) with the desired one (company's productivity goals), symbolized by the **balancing loop B1. task design**. These decisions aim to "close the gap" between goals and actual performance creating a balancing loop. However, managers should be aware that **task design** can also have a negative effect on human cognitive capacities. An incorrect task design can make the worker's attentional resources (human cognitive capacity) be below average. Causing *productivity* to be lower than expected, driving the company's current state further from goals and increasing the gap between these two states. This behavior is represented by **loop R1. Human factors**. **Task characteristics** are included in the diagram to symbolize **Performance Shaping Factors (PFSs) proper of the task** that define **the maximum productivity** and have an influence on **human cognitive capacities**.

The terms task design, task characteristics, human cognitive capacities are used as categories and do not represent variables in the model. Increasing task design is considered as increasing workload, working hours, diminishing breaks, etc. A decrement of human cognitive capacities is considered as workers having lower resources to devote to the task. Task characteristics are considered as factors proper of the task such as the degree of monotony or degree of complexity that affect productivity as workers need to put higher effort in them. They are considered to also affect human cognitive capacities as workers require extra resources to perform these tasks.

4.3 Formulation of a Simulation Model

This subsection aims to describe the System Dynamics model that was created. As previously mentioned, the construction of this model is based on a bio-mathematical model called "Fatigue Index".

The System Dynamics model contained in this work (including the model extension) comprises four sectors, illustrated in Figure 4. A **cognitive fatigue sector** is included, which includes the *cognitive fatigue* calculation as described in the **fatigue index**. This sector has an influence on the **effort sector** and the **manufacturing sector**. In the **effort sector,** *cognitive fatigue* defines the *initial effort incurred* and *maximum incurred effort* and in the **manufacturing sector**. C*ognitive fatigue* affects *productivity,* making it being below its normal values as higher *fatigue* is presented. The **effort sector** influences the **cognitive fatigue sector** by increasing the normal value of *fatigue increments* per unit of time when in the presence of *effort incurred*. The **effort sector** affects the **manufacturing sector** by increasing *productivity* as *effort incurred* increases. Finally, the **manufacturing sector** has feedback on the **cognitive fatigue sector** via decisions taken by managers and by the work pressure employees have. The **learning curve sector** represents the *knowledge* gained by employees as more production is undergone and this higher level of *knowledge* results in less *time to produce a unit* and a higher *productivity* per unit of time in the **manufacturing sector** which once again increases the level *knowledge*.

A detailed description of the model will be given in the following paragraphs. First, a brief overview of this model will be given. Second, the translation of this model into System Dynamics will be described. Third, an explanation of the manufacturing sector included in the model to show the effects of *cognitive fatigue* on productivity will follow. Finally, the two extra sectors that were added to the model to obtain a more accurate result will be described.

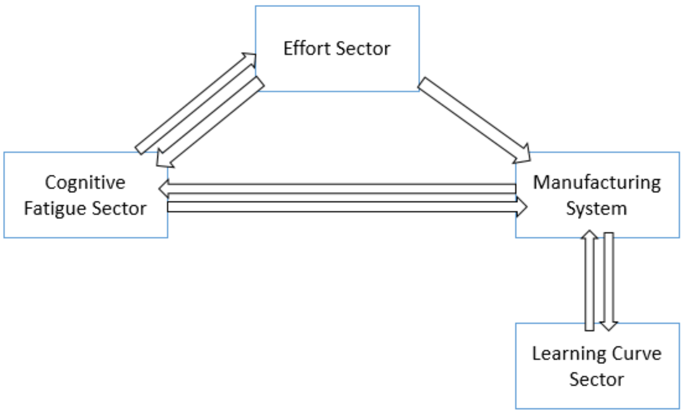

Figure 4. Model sectors and relationships between them.

4.3.1 The Fatigue Index

> *"Fatigue is the decline in mental and/or physical performance that results from prolonged exertion, lack of quality sleep or disruption of the internal body clock. The degree to which a worker is prone to fatigue is also related to workload. For example, work that requires constant attention, is machine-paced, complex or monotonous will increase the risk of fatigue" (HSG, 2006).*

The **Fatigue Risk Index** documentation (Spencer, Robertson, & Folkard, 2006) was analyzed with the objective of constructing a System Dynamics version of this model. Nevertheless, during the construction of the model, the information provided in the documentation proved to be not sufficient as specific detail for the computation of most of the factors or values was omitted. The authors were contacted in order to cover these information gaps but no response was provided. As a consequence, the documentation of a previous version of the Fatigue Risk Index, the **Fatigue Index**, was used as a basis for constructing the model.

The **Fatigue Index** was originally created with the aim to assist corporations in the labor of risk assessment of safety-critical work. It was determined by assessing the impact on fatigue of changes in working time patterns of the workers. An increase in the level of fatigue would indicate the need for more detailed assessments of risks. Five factors are including in the calculation of the fatigue level: time of day, shift duration, rest periods, breaks and cumulative fatigue. the four first factors are considered as short-term fatigue (fatigue generated during a shift) and the fifth (cumulative fatigue) aims to represent fatigue generated over more than one shift (E.g. the effect of five-night shifts in a row). The creation of the index was commissioned by the Health and Safety Executive (HSE) of the UK. The research was undergone by the Defense Evaluation and Research Agency (DERA) and the Center for Human Sciences (CHS). Both expert opinions from shiftwork research and the experience of working practices in the British Industry were used. The fatigue scores provided by the **Fatigue Index** were compared by the authors with the output from the CHS alertness model (Rogers, Spencer, & Stone, 2009) for validation purposes. The previous comparison was successful, with no major discrepancies.

The **Fatigue Index** is considered within the category of bio-mathematical models. Biomathematical models are used to obtain quantitative estimates of the overall state of individuals' cognitive system (Gunzelmann, Gross, Gluck, & Dinges, 2009). They are based on empirical studies that investigate sleep-related factors and time-related factors. These two categories constitute the basic elements included in bio-mathematical models, nevertheless more complex models exist within this category. Williamson, Lombardi, Folkard, Stutts, Courtney, and Connor (2011) not only considered homeostatic factors (sleep-related factors) and circadian influences (time-related factors) as major sources of fatigue leading to accidents and performance decrements. They included the nature of the task (e.g., duration, workload and monotony) as a relevant factor to study. A review of Fatigue a review of bio-mathematical models was committed by The Civil Aviation Safety Authority from Australia and highlighted that a limitation and expected additional input for them is related to task/context factors and individual factors. Task/context factors refer to workload or level of attention required, frequency and duration of breaks. Factors related to individuals are phenotype (morning / evening person), sleep length, commuting time, etc. (CASA, 2014). The Fatigue Risk Index was considered as relevant as it covers: homeostatic factors, circadian influences, the nature of the task and task/context factors.

4.3.1.1. Representation of time events in the model

As pointed out before a fatigue model includes not only factors related to the task but also homeostatic factors and circadian influences play an important role. The **Fatigue Index** relies on time-related factors such *shift start and end time, time of the day, break length*.

Discrete events are events that happen at specific points in time. For example operators take breaks, shifts change, and so forth (Sweetser, 1999). For modeling time-related factors (daytime, weekday/weekends, breaks/on task status) the procedure described by Coyle (1985) about modeling discrete events in a manufacturing setting served as a basis. Coyle's model involved a production setting in which discrete events such as two production shifts and machine breakdowns took place. This approach was adapted to the **Fatigue Index** needs, a more detailed description is given in the section “Annex 2. Time structures” of this document.

4.3.1 Fatigue Index – Cognitive Fatigue Sector

As mentioned before the **cognitive fatigue sector** of the model was constructed using the fatigue index as a source. The five factors included in the index make up the entire sector as portrayed in Figure 5. These five factors interact together to give a value for *cognitive fatigue*. The detailed structure for the calculation of each factor will be explained separately.

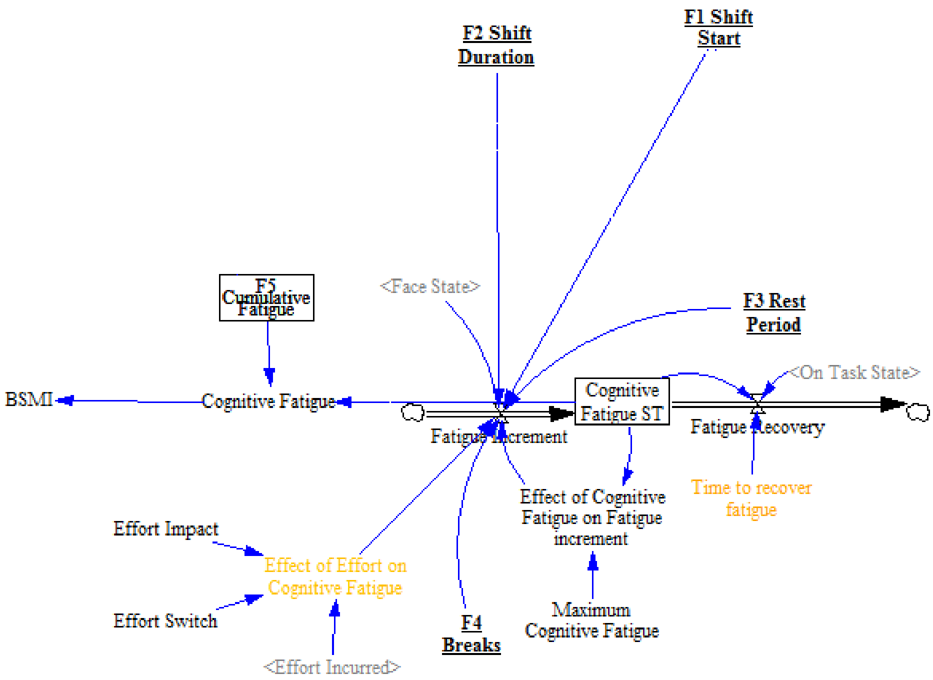

Figure 5. Cognitive Fatigue and BSMI calculation Structure

Cognitive Fatigue

The main variable in this sector is *cognitive fatigue*, its value is obtained by the addition of *factor 5 cumulative fatigue* and *cognitive fatigue ST* (short term). *Cognitive fatigue ST* (short term fatigue) and *factor 5* were treated as separate stocks as their recovery rate is due to different factors. *short term fatigue* gets replenished after a normal rest period, while *cumulative fatigue* depends on continuous full days without being involved in work activities. the scale used in the case study used to verify the model is the Perceived Mental Exertion scale (BSMI). In order to compare the results of the model with the case study, a conversion was necessary. the value of *cognitive fatigue* given by the model is multiplied by 1.5 as the scale of BSMI goes from 0 to 150 and the *cognitive fatigue* scale of the model from 0 to 100.

Cognitive Fatigue = (Cognitive Fatigue ST+F5 Cumulative Fatigue)

*BSMI = Cognitive Fatigue*1.5*

Cognitive Fatigue ST (short term)

The *short term fatigue* score is calculated by adding factors one to four together and multiplying this value times the *effect of effort on cognitive fatigue*. The accumulation of the factors was set for the entire shift, even during breaks, as factors F1, F2, F3 are calculated for the entire shift as are independent of the amount of breaks and its length. F4 creates a higher *fatigue increment per period* whenever a break is not taken after a long time-on-task on activities that require sustained attention according to the period of the day and whenever a break happens this accumulation stops. Finally, the *effect of cognitive fatigue on fatigue increment* aims to protect the level and keep the values in the adequate range.

*Fatigue Increment = (((F2 Shift Duration+F1 Shift Start+F3 Rest Period+F4 Breaks)*Effect of Effort on Cognitive Fatigue)*(1-(1-Face State))*Effect of Cognitive Fatigue on Fatigue increment)*

The **Fatigue Index** doesn't provide explicit information about the recovery of *short term fatigue*, nevertheless for a continuous/dynamic behavior a *fatigue recovery* rate needed to be included. the only information provided by the documentation is that *fatigue recovery* happens during the rest period. A value of 24 hours was used to account for this. The objective of this outflow is to set back the value for *cognitive fatigue ST* to zero whenever the shift is over, so that the next shift the stock starts in zero. Nevertheless, if the model was adapted to be used for prediction, this value would need to be revised.

The objective of the *effect of effort on cognitive fatigue* parameter is to increase the *fatigue increment* according to the *effort incurred*. No exact values were found in the literature for representing this effect. For now, effort incurred (0 to 1) would make the fatigue increment higher according to the number set on *effort impact*. If *effort impact* is set at two, *fatigue increment* for that period will be increased by the number given by the multiplication of *effort impact* and *effort incurred*. In such a way that when the *maximum effort incurred* is presented (1), the *fatigue increment* will be multiplied by the number set for *effort impact*. Whenever *effort incurred* is lower than 1, only a fraction of the value set for *effort impact* will be considered for the increment.

F1 - Time of the day

This factor gives an initial fatigue value according to the shift start time. The value contributed by the start time is higher for shifts starting at early hours in the day (before 9 hrs.) and for shifts starting in the afternoon (after 14 hrs.). The level of cognitive workload has an effect on this fatigue value, with high levels of workload (complex work, with time constraints) the value is increased by four units during the entire shift (this value is divided by the shift length in order to get fatigue units per hour). The values provided by the fatigue index for different times of the day includes circadian rhythm influences on alertness. The previous is represented in the model by using a non-linear function in the model.

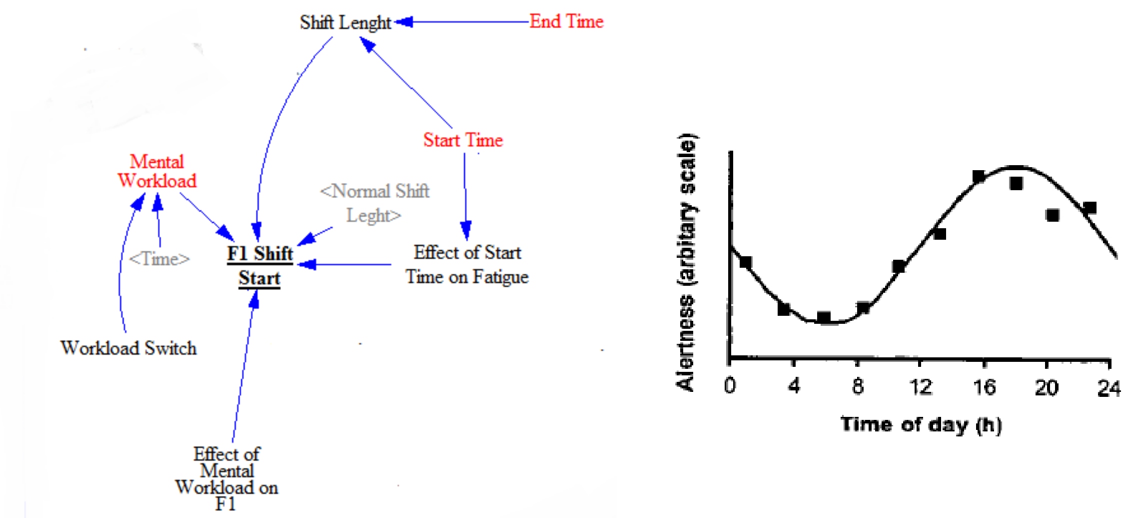

Figure 6. Effect of Start Time on contribution to Fatigue

Left: Model Structure for representing Factor 1. Right: Representation of circadian rhythm according to the time of the day. Source (Right Image): **Fatigue Index** documentation. (Rogers et al., 2009)

The F1 score for each shift, according to the time of day at which it starts, is given in the table below.

Start time	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00
score	13	13	13	12	12	11	9	7

Start time	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00
score	4	2	1	1	1	2	3	4

Start time	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
score	5	7	10	11	12	13	14	14

Table 3. Contribution to Fatigue per shift at different shift start times

Source: **Fatigue Index** documentation. (Rogers et al., 2009)

A nonlinear function was used to assign the fatigue value according to the start time. The duration of the shift also has an effect on this value. For shifts shorter than eight hours, a proportion of the score has to be subtracted. The values given in the documentation of the **Fatigue index** correspond to the total value for a day, to obtain the value for fatigue per hour, the values were divided by the number of hours of a normal shift (*normal shift length*: eight hours).

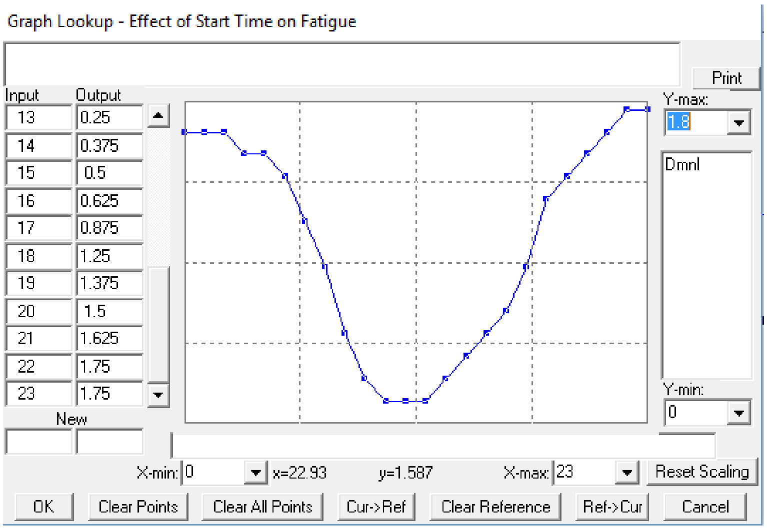

Figure 7. Non-Linear function. Values used to represent the effect of shift start time on fatigue increments per hour

The variable "*normal shift length* "is used to calculate the F1 fatigue value increment per hour when the shift is shorter than eight hours with the purpose to decrease an appropriate proportion of the score depending on *shift length*. The actual *shift length* value avoids the representation of the decrement in the F1 factor for shifts smaller than 8 hours:

Assuming high workload (four fatigue units), a shift starting at 15:00 hours (four fatigue units), a *normal shift length* of eight hours and an actual *shift length* of six hours.

*F1 = (.5*Mental Workload value + F1)/ Normal shift length (8) = (4+4)/8 = 1 fatigue units/hour*

Value accumulated after 6 hours: 6 fatigue units

*F1 = (.5*Mental Workload value + F1)/ Shift length (6) = (4+4)/6 = 1.33 fatigue units/hour*

Value accumulated after 6 hours: 8 fatigue units

*6 hours corresponds to 75% of the normal shift length and the value for fatigue for 6 hours then should be (8 fatigue units *.75 = 6 fatigue units)*

To final formula that gives the *Cognitive Fatigue* value per hour considering the level of workload and the *Effect of Start Time On Fatigue* is:

*F1 = (0.5*Mental Workload value + Effect of start time on Fatigue)/Shift Length*

The effect produced by *Mental workload* in the model can be activated as an endogenously or manipulated exogenously. It is activated endogenously by comparing in the **manufacturing sector** the actual productivity against the desired productivity. Nevertheless, it can also be treated as an exogenous factor for those cases in which the information about desired productivity is not available or the level of cognitive workload varies within the shift as in the case study used for verification of the model. The previous is enabled with a switch that when having the value of zero disconnects this variable from the manufacturing sector. A non-linear function is included to represent variations of workload within a shift. A value of zero would represent low workload and a value of one would represent high workload. A value of one can be specified for specific times within a shift with high workload. If a situation in which low workload exists the value of the variable is zero, so no extra fatigue units are added. Whenever the value of the variable is one a daily increment of four units is added to factor F1 (.5 fatigue units per hour). The lowest possible value per day for this factor is one (shifts starting between 10 hrs. and 12 hrs.) and the highest value is fourteen for shifts starting between 22 hrs. and 24 hrs. If a high level of workload exists, the lowest value for the factor would then be five (1+4) and the highest value eighteen (14+4) for shifts of eight hours of more.

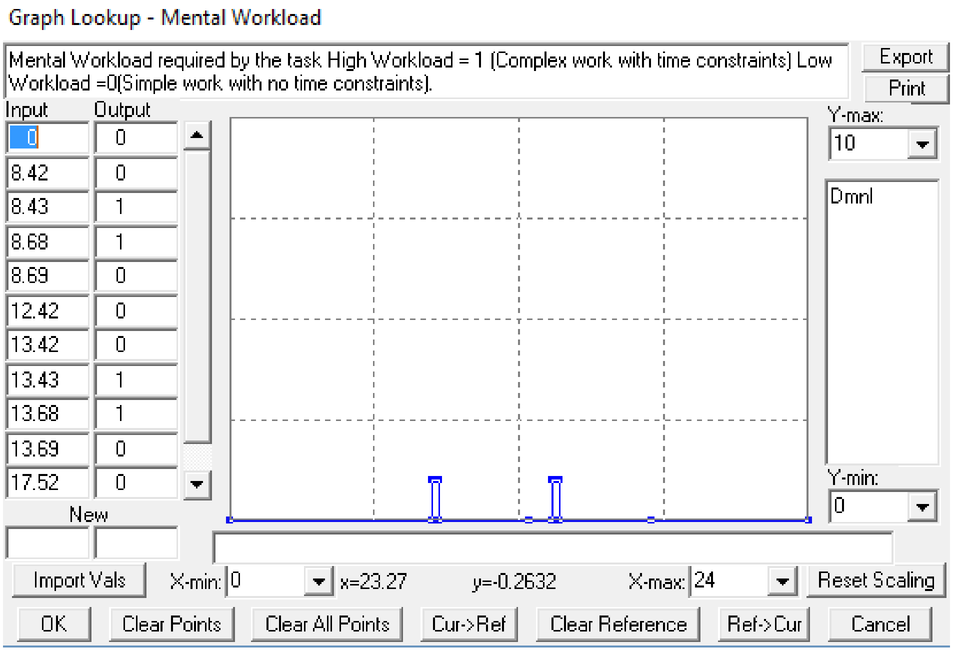

Figure 8. Example of non-linear function for setting mental workload as an exogenous variable

In Figure 8 it can be noted that from hour 8.43 to 8.68 mental workload is activated. The time notation used is hours. Minutes are expressed in a decimal hour notation. Sixty minutes are equivalent to one hour. Whenever an event happens at a specific minute within an hour, the equivalent of that minute in decimal hour notation has to be used. For example, for representing an event at 8:15 hrs., the fifteen minutes after eight need to be divided by sixty. With this, the value will already be shifted to a decimal hour notation. This value then just needs to be added to the total hours.

Conversion of 8:15 hrs. to decimal hour notation

Fifteen minutes in decimal hour notation = 15/60 = .71

Result = 8.71

F2 - Shift duration

To calculate the contribution of shift duration to fatigue, both *shift length* and the *start time* are considered, e.g. a shift starting at seven hrs. with a duration of eight hours will not contribute to fatigue whereas a shift starting at the same time but with a duration of nine hours contributes with one fatigue unit during the entire day. When *mental workload* equals one (high level) the contribution of this factor to *cognitive fatigue* increases. It produces a 30% increment of the original value. The calculation of this factor accounts for homeostatic factors and nature of the task (complexity, time constraints) by the effect of mental workload, the values were obtained directly from the documentation of the **Fatigue Index**. A normal shift of eight hours doesn't contribute to fatigue score. The contribution of shifts longer than eight hours is represented by a nonlinear function.

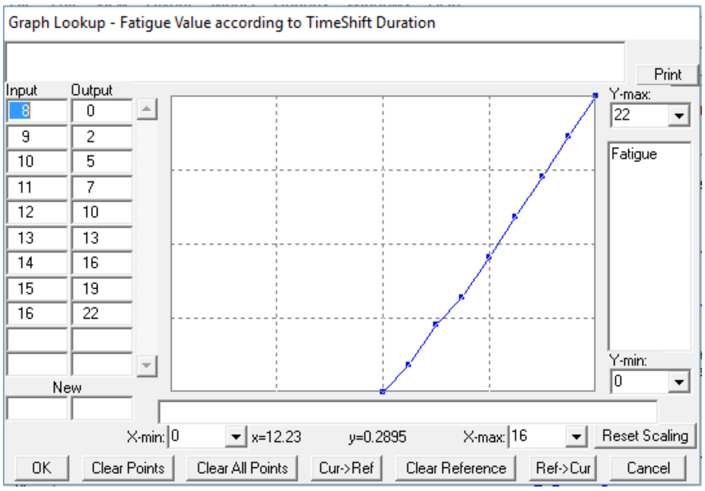

Figure 9. Non-Linear function used to determine the contribution to fatigue per shift for diverse shift lengths

The fatigue score for F2 is given for the entire shift, this value is divided by the actual shift duration to get the fatigue score per hour. In the notes provided by the index it was stated that if overtime happened in a shift, this would be reflected in the index by extending the shift duration. The model accounts for it, as the start time and end time for each shift have to be provided, so shift duration considers not the normal shift duration but the actually worked time.

High workload. *F2 = (Fatigue Value according to Time Shift Duration*1.3)/Shift Length*

Low workload. *F2= Fatigue Value according to Time Shift Duration/Shift Length*

4.1.2 F2 – Shift duration

The F2 score, relating to the time the shift starts, is given in the table below.

Start time	Shift duration (hours)								
	8	9	10	11	12	13	14	15	16
0:00	0	2	5	7	10	13	16	19	22
1:00	0	2	5	7	10	13	15	18	21
2:00	0	2	5	7	10	12	15	18	21
3:00	0	2	4	7	9	12	15	17	20
4:00	0	2	4	6	9	11	14	16	19
5:00	0	2	4	6	8	10	13	15	18
6:00	0	1	3	5	7	9	11	13	16
7:00	0	1	2	3	5	7	9	11	13
8:00	0	0	1	2	3	4	5	7	9
9:00	0	0	1	1	2	3	5	6	8
10:00	0	0	1	2	3	4	5	7	9
11:00	0	0	1	2	3	5	7	9	11
12:00	0	1	2	3	4	6	8	11	13
13:00	0	1	2	4	6	8	10	13	15
14:00	0	1	3	5	7	9	12	14	17
15:00	0	2	3	6	8	10	13	16	19
16:00	0	2	4	6	9	12	15	17	20
17:00	0	2	5	7	10	13	16	18	21
18:00	0	2	5	8	10	13	16	19	22
19:00	0	2	5	8	11	14	16	19	22
20:00	0	3	5	8	11	14	17	20	23
21:00	0	3	5	8	11	14	16	19	22
22:00	0	2	5	8	11	13	16	19	22
23:00	0	2	5	8	11	13	16	19	22

Table 4. Fatigue Score according to Shift start time and Shift duration

Source: **Fatigue Index** documentation. (Rogers et al., 2009)

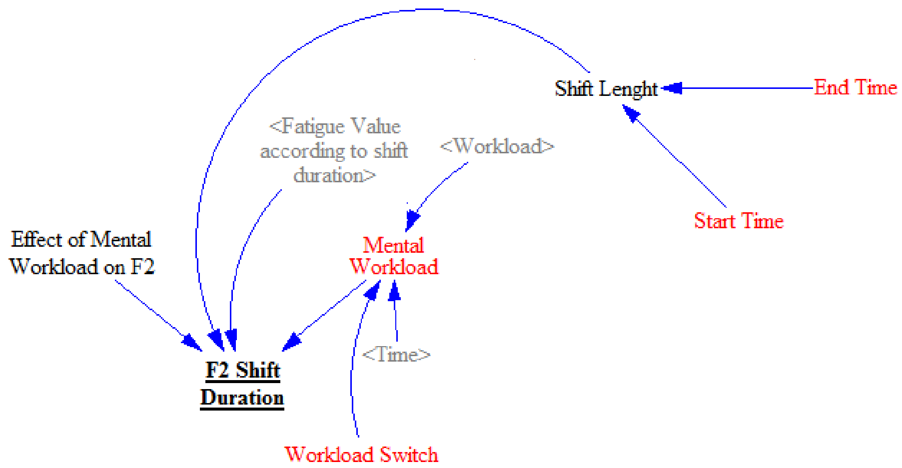

Figure 10. Factor 2 Shift Duration

The lowest possible value for this factor is zero for shifts of eight hours and the highest possible value is twenty two for shifts of twelve hours starting between 22:00 and 01:00 hours.

F3 - Rest period

A rest period should have the necessary length for a worker to recover and start the next shift without fatigue. The worker must have enough time for a normal sleep period after considering the time required for covering its family responsibilities and commuting time. The data used for the calculation of this factor in the **Fatigue Index** comes from studies in aircrew operations, where it was observed that the amount of sleep depended not only on the length of the rest period but also on the duty start time. The study covered times between 04:00 and 22:00, the fatigue contributions during these times were calculated based on the information available and for periods between 22:00 hrs. a linear interpolation was made and the degradation associated with time since sleep in the model was used to calculate the effect over different shift lengths (Rogers et al., 2009).

The contribution to fatigue given by a rest period is defined by the time at which the rest period of the worker ends (Start of shift time minus commuting time), the hours needed for a full rest and the exceeding shift time of the day it is calculated. The time at which the rest period ends is assigned to a category that will indicate: 1) hours needed for a full rest 2) contribution to fatigue of the lacking hours for full rest “Rest Period Score (RSP) (See Table 5).

End of rest period	RSP score
04:00 – 08:00	2 for every hour by which the rest period is shorter than 13 hours
09:00 – 12:00	2.6 for every hour by which the rest period is shorter than 12 hours
13:00 – 18:00	3.5 for every hour by which the rest period is shorter than 13 hours
19:00	2.2 for every hour by which the rest period is shorter than 15 hours
20:00	1.8 for every hour by which the rest period is shorter than 17 hours
21:00	1.5 for every hour by which the rest period is shorter than 19 hours
22:00 – 03:00	1 for every hour by which the rest period is shorter than 20 hours

Table 5. End of rest period times, rest period required length and Rest Period Score

Source: **Fatigue Index** documentation. (Rogers et al., 2009)

Note: when the actual rest period is longer than the required length for full recovery the RSP score is zero.

The end time considered to calculate the end period should be the one from the previous period. A pipeline delay of 24 hours was used to account for this effect. The rest period accounts for Personal time plus commuting time, this values will be exogenous values in the model.

The formula used for calculating factor F3 was obtained directly from the Fatigue Index and the value obtained was distributed throughout a shift. Every hour by which the rest period is shorter than required will contribute to the F3 fatigue score by the number given by the **Rest period score**. This number is then multiplied by the number of *exceeding hours* of the actual shift multiplied by ten (value indicated by the fatigue index documentation). The result of this operation is then divided by twenty (value indicated by the fatigue index documentation[1]) and this will give the total fatigue score according to the rest period.

For obtaining the fatigue contribution of this factor per hour the shift length is used under the assumption that this value accumulates throughout the entire shift (actual working times, not normal shift length).

The final formula used to compute this value is:

*F3 = ([(Rest period score * Rest period Lacking hours) * (10 + number of exceeding hours)] /20) / Shift Length*

[1] As previously mentioned, Rogers (2009) based the calculation of the values for factor 3 on an aircrew study. The multiplication by ten and division by twenty were used to correct the value computed and make it applicable to any start time. The results of the study only covered times between 22:00 and 04:00 hrs.

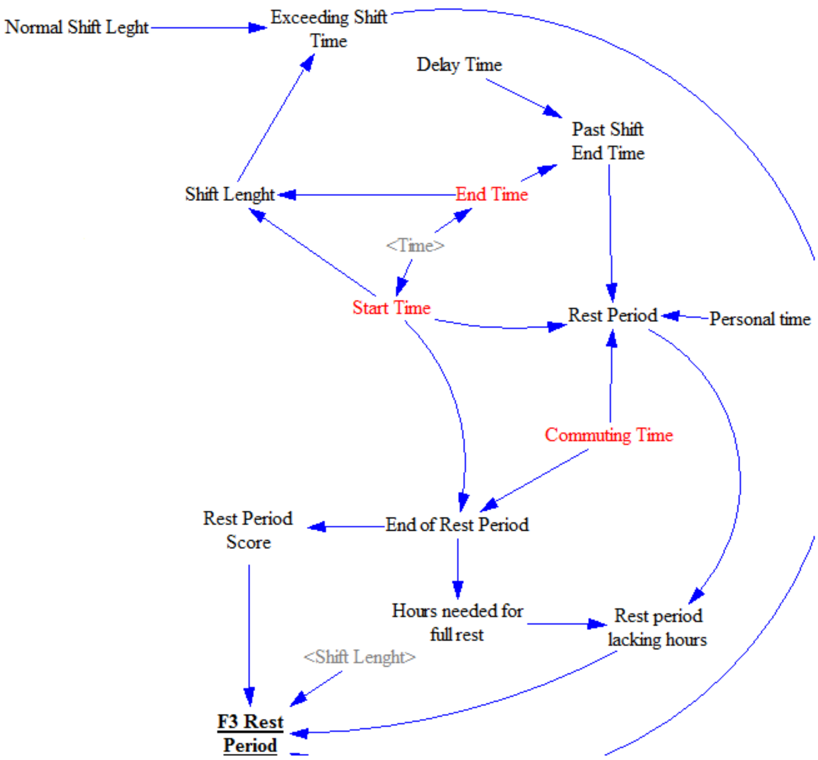

Figure 11. Factor 3 Rest Period model structure

The minimum value that this factor can have is zero if the rest period was longer than the required hours for full rest and the maximum value for a day is 18.4. The value of this factor is calculated in the following way:

*F3 = [{ (Rest period score * Rest period Lacking hours) * (10 + number of exceeding hours) } / 20] / Shift Length*

*F3 = [{ (3.5 * 7) * (10 + 8) } /20] / 13 = 22 fatigue units per day*

F3 = 18.4 / 13 = 1.69 fatigue units per hour

Highest Rest period score = 3.5 each hour in which the rest period is shorter than 13 hours, given by the original data for the index construction

Rest period lacking hours = (Rest period required hours (13) - (Minimum sleep time per night for maintaining performance (4) + commuting time (1) + time for personal activities (1))

Rest period lacking hours = 13 – 6 = 7 hours

The minimum sleep time per night for maintaining performance was obtained from the results showed by Belenky, Wesensten, Thorne, Thomas, Sing, Redmond et al. (2003) of a sleep restriction and recovery study, the minimum sleep time per night at which alertness and performance can be maintained at a stable but reduced level is four hours.

Number of exceeding hours of the shift = Maximum shift length – Normal shift = 8

16 – 8 = 8 hours

Maximum shift length = 13 hours is the maximum allowed hours at work in The Netherlands (MSAE, 2010) but the index includes values up to sixteen hours so sixteen hours were used.

F4 - Breaks Factor

This section of the model aims to represent the fatigue produced by periods of work that demand continuous attention (e.g. driving tasks, monitoring). The data for the development of this component in the **Fatigue Index** comes from an experimental study regarding performance decrements associated with continuous periods of attention at different times during the day. This factor is intended to account for work in which momentary lapses of attention could increase the risk of an accident.

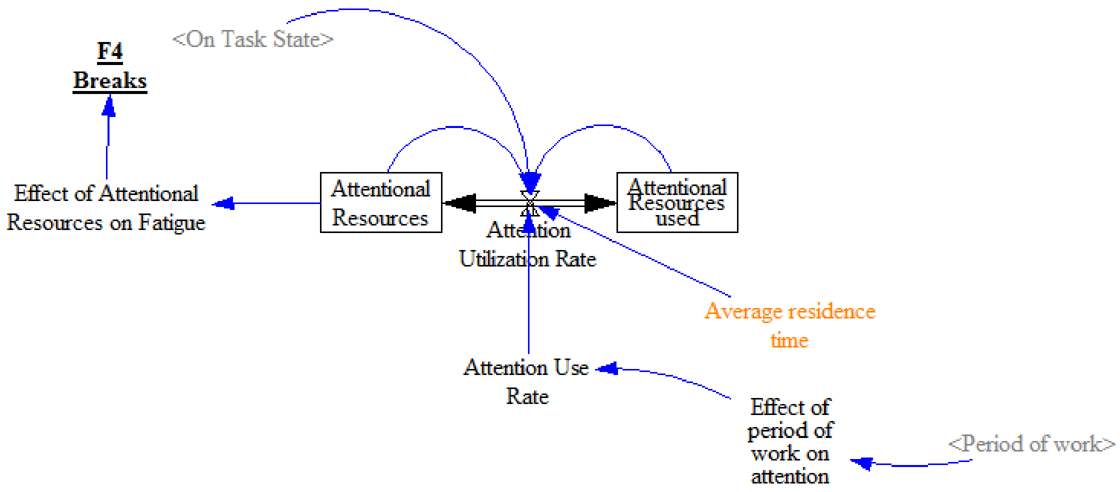

Figure 12. F4 Breaks structure

F4 = Effect of Attentional Resources on Fatigue. (The detail of this effect will be described in the following paragraphs as it is not a straightforward calculation)

The factors considered for the calculation of this value are sub-period of the day and time-on-task/breaks represented by two stocks labeled attentional resources. The day is divided into four sub-periods: morning, afternoon, evening and night according to the time of the day (see Table 4) and each sub-period is assigned a number from one to four. This number will then serve to determine the attention utilization rate.

Shift sub-period Value	Shift sub-period	Time	Effect of period of day on Attention Utilization Rate	Attention Utilization Rate
1	Morning	06:00-14:00	1	0.125
2	Afternoon	14:00-17:00	2	0.25
3	Evening	17:00-01:00	1	0.125
4	Night	01:00-06:00	4	0.5

Table 6. Shift sub-periods classification and Values used for computing the accumulation of fatigue

During morning/evening shifts a worker can maintain sustained attention for a longer period compared to the level he could do in the afternoon. In turn, this level of sustained attention (afternoon) can be longer in comparison to that of the night period. In other words, if a worker needs to keep sustained attention for a period longer than a hundred and twenty minutes in the morning/evening this will lead to the accumulation of *cognitive fatigue*. In the afternoon the effect on fatigue will happen after sixty minutes and at night after thirty minutes. If a break of at least fifteen minutes is taken before these times, the capacity of the worker to sustain attention is restored and no contribution to fatigue occurs.

Time on Task	Fatigue contribution/ hour			Attentional Resources Level		
Mins since last break	Morning/ Evening	Afternoon	Night	Morning/ Evening	Afternoon	Night
30-60	0	0	0.5	1	1	<,75
60-120	0	0.5	1	1	<,75	<,5
120-180	0.5	1	1	<,75	<,5	<,25
180-240	0.5	1	1.5	<,5	<,25	<0,0671
240-300	1	1	1.5	<,25	<,25	<0,0671
300-360	1	1	1.5	<,25	<,25	<0,0671

Table 7. Fatigue Contribution per hour according to period of the day and time-on-task and Attentional Resources level on a 0 to 1 scale

For modeling purposes a stock labeled "*attentional resources*" was used to represent the effect of the elapsed time working on a task since last break (time-on-task) on activities that require sustained attention. Attention units are consumed whenever the variable "on task" state equals one (meaning that there is a shift and no break is happening). This consumption happens at a rate of .125 attentional resources per hour for morning and evening sub-periods, it will double for the afternoon sub-period (rate of .250) and triple for the night time (rate of .5). The previous is illustrated in Figure 15, where a graphical representation of the effect on the level of two different depletion rates is given. *Attentional resources* are considered to be limited following limited resources theories (Langner & Eickhoff, 2013). It is represented with a minimum value of zero and a maximum value of one. The depletion rate was selected in such a way that in the morning and evening after 120 minutes on the task a consumption of 25% of the resources has happened, leading to a value of .75 of *attentional resources* and causing a *fatigue increment* of 0.5 per hour. After four hours working with sustained attention, 50% of the resources have been used with this rate and the *effect of attentional resources on fatigue* would then be 1 (See table 5). The same procedure applies for afternoon and night times.

Attentional Resources Level	Fatigue Increment per hour
<,75	0.05
<,5	1
<,25	1
<0,0671	1.5

Period of the day	Attention Utilization Rate
Morning/Evening	0.125
Afternoon	0.25
Night	0.5

Table 8 Fatigue Increment per hour at different Attentional Resources levels.

Note that the depletion rate for attention resources values was chosen with the only purpose of the representation of the effect of "time-on-task/breaks" on fatigue for activities requiring sustained attention as indicated by the **Fatigue Index**. The level *Attentional Resources* was also scaled to produce the necessary *fatigue increment* per hour but this might not have the same scale as actual *attentional resources* in a human being. A state of zero attentional resources will only mean that the *highest fatigue increment rate* will happen but it is not intended to portray a hypo-vigilant state (a state with no longer acceptable level of performance). When a break of fifteen minutes is taken *the attentional resources* levels will be completely replenished according to data provided by the original index documentation. It is important to highlight that this does not mean that the worker would have recovered completely his mental processing capacities. The accumulated fatigue during the shift will continue to reduce productivity. The replenishment of attentional resources is only temporary and only represents no further additions to fatigue by this factor. Nevertheless, when the break finishes the depletion of this level will start once again and contribute to fatigue increments whenever the maximum number of minutes without a break is surpassed.

The rate for the recovery of *attentional resources* was designed in such a way that after a 15 minutes break the stock was replenished. After five adjustment times 99.3% of the gap (value between attentional resources used and zero) will be covered (Sterman, 2000: 279). As mentioned before this stock has a maximum value of one and should not have negative values. When the *Attentional Resources* level is lower than the required *attention utilization rate,* the minimum of both values will be the one used for the attention utilization rate. For an example of how this component works please refer to Annex 3.

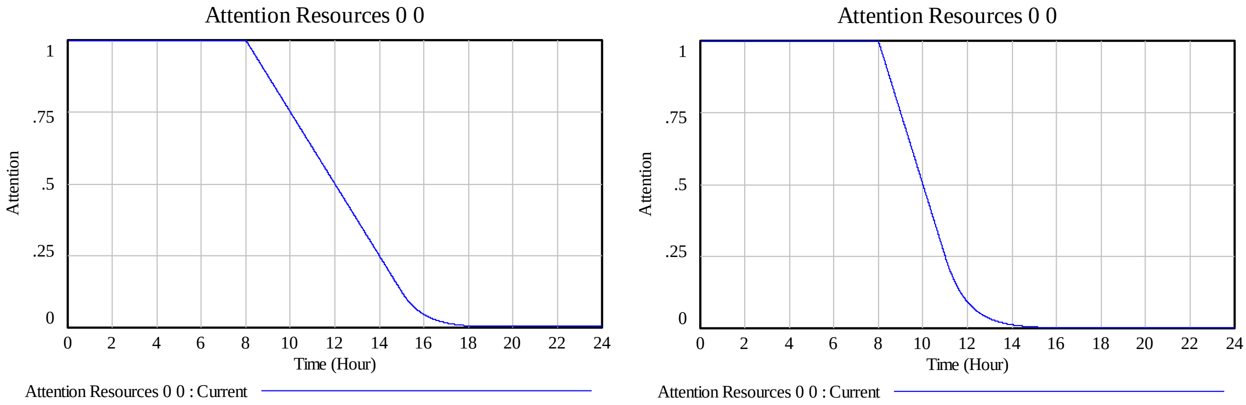

Figure 13. Attention Resources depletion for a shift starting at 8 am with a .125 depletion rate (left) and a .250 depletion rate (right)

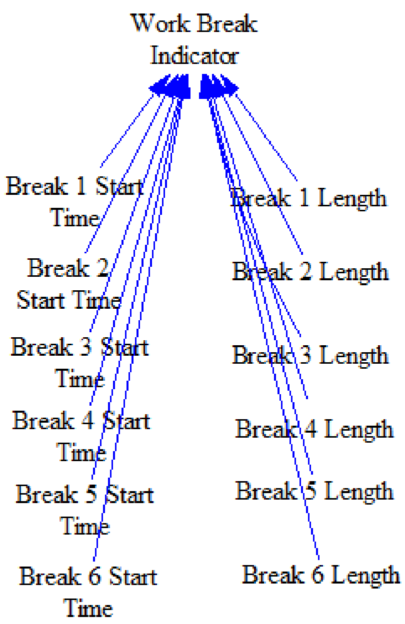

Figure 14. Work Break Indicator Structure

The model includes the possibility of indicating six breaks (this structure can be extended), the *break start time* and the *break length* of each break can be specified. work break indicator is a variable with possible values of one or zero representing if the work status of the operators. Working status "On task" = 1 or if a break exists the value would be zero This structure was created using the method described by Coyle (1985) for the timing of main events.

The minimum value for **Factor 4 - Breaks** is zero. This situation can happen in morning, afternoon and evening shifts, whenever a break is taken before the period of sustained attention exceeds the limit. The maximum value would be 18 fatigue units per day, on average 1.39 per hour. It was calculated for the period of work in a night shift with a shift length corresponding to the longest period of work previously stipulated for the calculation of Factor 3 (13 hours) and no breaks in between.

F5 - Cumulative component

This factor represents the effect of consecutive shifts during the same period of the day. The number of nights, early, late, day and day off shifts in a row will contribute to the *Cumulative Fatigue* rating (See Figure 15). Each consecutive period of 24 hours is assigned to the following categories:

- Night – part of the shift covers anytime between 02:30 and 04:30
- Early – shift starts between 04:30 and 07:00
- Late – the shift ends between 00:00 and 02:30
- Day – any other shift
- Day off – no shift during that period

Each 24-hour period is then scored as follows:

Night:

no. of nights in sequence	1	2	3	4	5	χ6
Score	5	4	3	2	1	0

Early:

no. of earlies in sequence	1	2	3	4	5	χ6
Score	3	2	2	1	1	0

The score is reduced by 1 for any shift starting between 06:00 and 07:00

Late:

no. of lates in sequence	1	2	3	4	5	χ6
Score	3	2	2	1	1	0

The score is reduced by 1 for any shift ending between 00:00 and 01:00

Day:

no. of days in sequence	1	2	3	4	5	χ6
Score	0	0	0	0	0	0

Day off:

no. of days off in sequence	1	2	3	4	5	χ6
Score	-6	-4	-4	-4	-4	-4

A score of 0 is given to a day off that is contained within a rest period of less than 30 hours

Figure 15. Factor 5 Cumulative Fatigue Scores per days of sequential shifts with during same period of the day

To obtain the final Cumulative Fatigue level (F5) the values of each *effect (early starts, late starts, night shifts and days off*) are added together:

IF THEN ELSE (F5 Cumulative Fatigue<=0,

MAX(((Effect of day's off on fatigue+Effect of early and late starts on Fatigue+Effect of night shifts on fatigue)/Hours per day),0),

((Effect of day's off on fatigue+Effect of early and late starts on Fatigue+Effect of night shifts on fatigue)/Hours per day))

For the detail of how the effect of *cumulative (early starts, late starts, night shifts and days off)* is calculated please refer to the “Annex 2. Time structures” section of this document

After the addition of the effects is calculated the total *cumulative fatigue score* (fatigue units) for that shift is obtained. In order to obtain the inflow for the stock (fatigue units per hour), this value is divided by the number of hours per day. This formulation is built under the assumption that *cumulative fatigue* accumulates during the entire day as a consequence of the worker's schedule. An IF THEN ELSE function and a MAX function are used for ensuring that the stock doesn't go below zero.

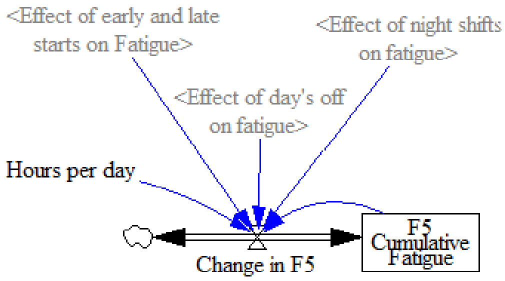

Figure 16. Model structure for F5 Cumulative Fatigue

Note: Cumulative Fatigue only works for shifts with a start and end on the same day, between 0 and 24 hrs. Modifications would need to be made to the model in order for the Cumulative Fatigue time structures and breaks time structures function for shifts starting one day and finishing the next.

4.3.2 Manufacturing Sector

To represent the effect of cognitive factors on *productivity* a **manufacturing sector** was included. This sector follows the normal structure of a manufacturing system and its structure is based on the structures given by Eberlein and Hines (1996). This sector has a level accumulating the work to do (*work in process inventory*) that is reduced when work gets completed (*completion rate*). The *completion rate* that workers can achieve is defined by the *productivity* of the workers, which is calculated after the effects of *learning, fatigue and effort* are considered. Nevertheless, not all the work will be done correctly (*correct work*). As workers' *cognitive fatigue* increases more errors are produced and the pieces have to go through the production process once again. To represent the previous, these incorrect pieces are accumulated in a level called *undiscovered rework*. After a certain time has passed they will return back to *work in process inventory* to be processed again. In the following paragraphs, a more detailed explanation of the previous will be provided.

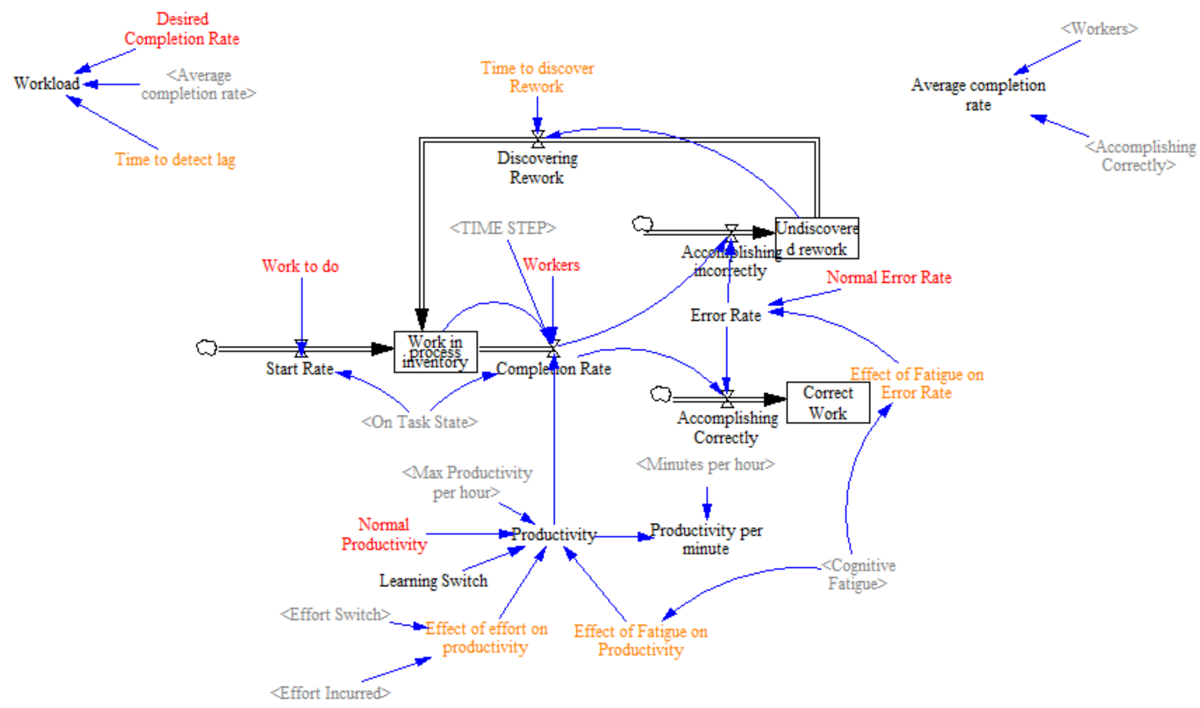

Figure 17. Manufacturing Sector Stock and Flow Diagram

Cognitive fatigue during a shift affects the workers' performance. This was represented in the manufacturing subsystem by an effect that alters both the value of *productivity* and the *error rate*. As cognitive fatigue increases, this effect becomes stronger. First, a higher level of *cognitive fatigue* results in a higher *effect of fatigue on productivity*, which would cause a lower level of productivity; second, a high level of *cognitive fatigue* would produce a higher *effect of fatigue on error rate*, resulting a higher error rate, causing more *undiscovered rework* and less *correct work.* The structure was based on the generic structures for constructing system dynamics models proposed by Eberlein and Hines (1996), which served as a source as well for the shapes of the non-linear functions used to represent both the *effect of fatigue on productivity* and the *effect of fatigue on error rate*. The values were scaled to fit the 0 to 100 scale of *cognitive fatigue*.

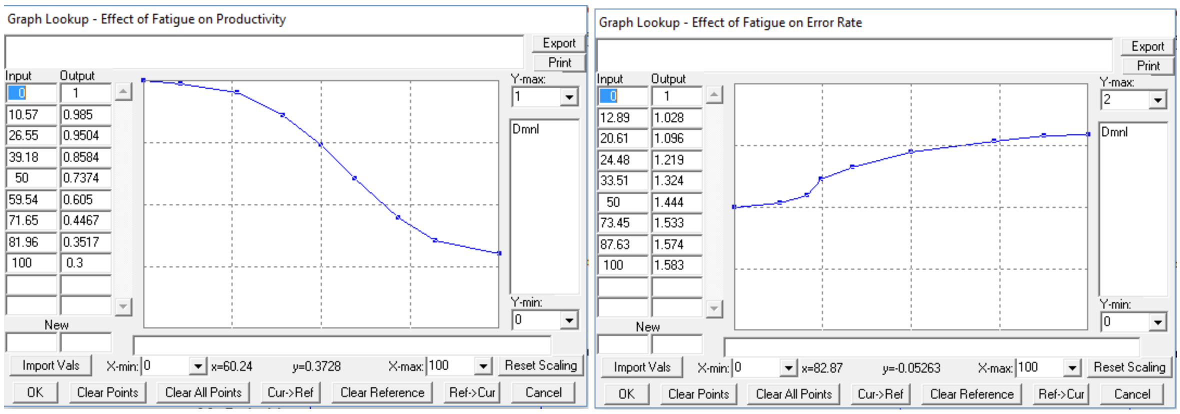

Figure 18. Non-linear Functions representing the effect of Cognitive Fatigue on Productivity and Error Rate

The *productivity* of the system is calculated per person per hour and is multiplied by the number of *workers* operating to get the total number of items produced per hour. When the number of items to produce (*work in process inventory*) is lower than *productivity*workers,* the number of items produced for the period will be limited by the available items. The *maximum productivity per hour* is derived from the **learning curve sector** and multiplied by the effect of effort and fatigue. Nevertheless, this will only happen when the *learning switch* is on (value of 1) when this switch is off (value of 0) then the value of *normal productivity* is used.

Productivity = IF THEN ELSE (Learning Switch=1,

*(Max Productivity per hour * Effect of Fatigue on Productivity) *(Effect of effort on productivity)*

*, Normal Productivity*Effect of Fatigue on Productivity*(Effect of effort on productivity))*

Completion rate is only active when the workers are "on task" state, meaning that they are not undergoing a *break*.

*Completion Rate = Min(Productivity*Workers, Work in process inventory/TIME STEP)*On Task State*

Not only *cognitive fatigue* has an effect on *productivity* but also *effort incurred* (the calculation of this factor is described in the section "4.4.3.2 Effort Sector"). The model operates at a 90% *productivity rate* when effort is equal to zero and at a hundred percent *productivity rate* when effort equals 1. An assumption was made to determine this value as no information was available in the data available from the case study data and no reliable value was found in the literature research. In the future, this value would need to be calculated using historical data from the case at hand.

A stock labeled *undiscovered rework* was included to account for the pieces or mistakes performed by operators. *Time to discover rework* represents the time it takes since a mistake is performed by an operator and how fast those items would take to take part in the production system again so that the error can be fixed, in the current system, this time, is set to 24 hours. The error rate is calculated by simply multiplying the *normal error rate* by the *effect of fatigue on error rate* described before.

Error Rate = Normal Error Rate(Effect of Fatigue on Error Rate)*

Finally, to determine the amount of workload, the *average completion rate* per worker per hour is compared to the *desired completion rate*. Managers don't detect immediately any discrepancy between this values, this is represented by a delay and can be specified by the *Time to detect lag* variable. When the *desired completion rate* is higher than *average completion rate* the worker will be working under pressure to achieve the objectives and high mental workload will be incurred.

Average Completion Rate = Accomplishing Correctly/Workers

Workload = (Average completion rate/Time to detect lag) /Desired Completion Rate

4.3.3 Extra sectors

Two extra sectors were included in the model to make up for the errors due to covariation for productivity. The assumption that *cognitive fatigue* leads to a lower productivity was proved to not be sufficient to explain the behavior of productivity after the model results were compared to the data from the case study. To explain why even if c*ognitive fatigue* increased, *Productivity* increased as well, the **Learning Curve Sector** and ***Effort Sector*** where included in the System Dynamics model.

The detail of why these sectors were included will be explained in the Validity Tests section, this section will only focus on its description.

4.3.3.1 Learning Curve Sector

The Structure of the **Learning Curve Sector** is based on the work of Givi, Jaber, and Neumann (2015a). The fatigue calculation part was omitted as this is already represented by the **Fatigue Index**. This sector aims to represent the *knowledge* gained after workers become more experienced, each item produced by workers will contribute to this. The time to pick an order diminishes as the employee accumulates *knowledge*, following the shape of a learning curve as shown in Figure 19. The *production time per unit* decreases at a fast rate when initial *knowledge* is obtained. However, the impact on *production time per unit* decreases as the employee becomes more experienced.

The *time to forget* and *effect of knowledge on time to produce* values were taken from the author's work. The value for the *effect of knowledge on time to produce* was set to ten percent of the original value as in the case study workers were supposed to already have had some training and practice.

Time to pick orders due to learning is calculated by elevating *knowledge* to the number given by the *effect of knowledge on time to produce* only when the worker has gained some experience. The formulation is simpler than the one described in the work of the authors because System Dynamics modeling allows to include an outflow for *knowledge* to represent the loss of *knowledge* when the worker is not on task and the model already accounts for units not produced during breaks.

*IF THEN ELSE (Knowledge<=0, Time to pick first order, Time to pick first order**

((Knowledge/Unit consistency Orders) ^ - Effect of Knowledge on time to produce))

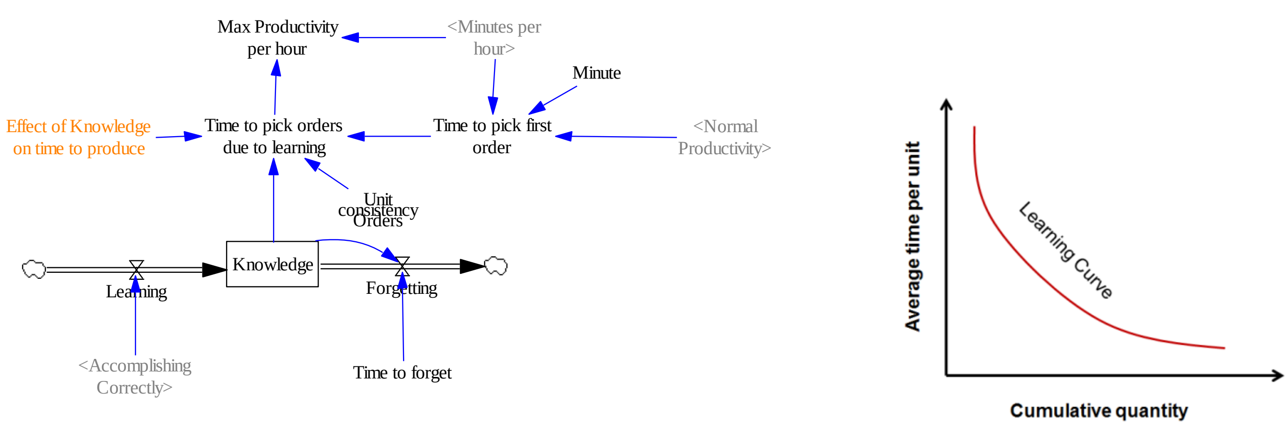

Figure 19. Left: Learning Curve Sector Stock and Flow Diagram. Right: Learning Curve Behavior

4.4.3.2 Effort Sector

The second sector added to the model has effects on both *Productivity* and *Cognitive Fatigue*. The structure of this sector is based on the work of (Stewart, Wright, Azor Hui, & Simmons, 2009; Stewart, Wright, & Griffith, 2006). The general structure of this sub-system is showed in Figure 20. This sector aims to describe how based on **task characteristics** such as *task difficulty* and *task relevance*, workers will determine the amount of effort they will exert in performing the task at hand (*effort incurred). Motivation* also plays a role to determine the amount of *effort incurred*.

The work of the previously mentioned authors is extensive and only the following three assumptions were adopted for constructing this sector:

- *Initial Effort* for the same task is perceived to be higher for a Fatigued Worker in comparison to the perception of a Rested Worker.
- *Task Importance* (success importance) determines the upper limits for *Effort*
- *Task difficulty* defines a point at which people suppress effort even if they are not fatigued, it is also the point at which success is seen as not further possible or excessively difficult.

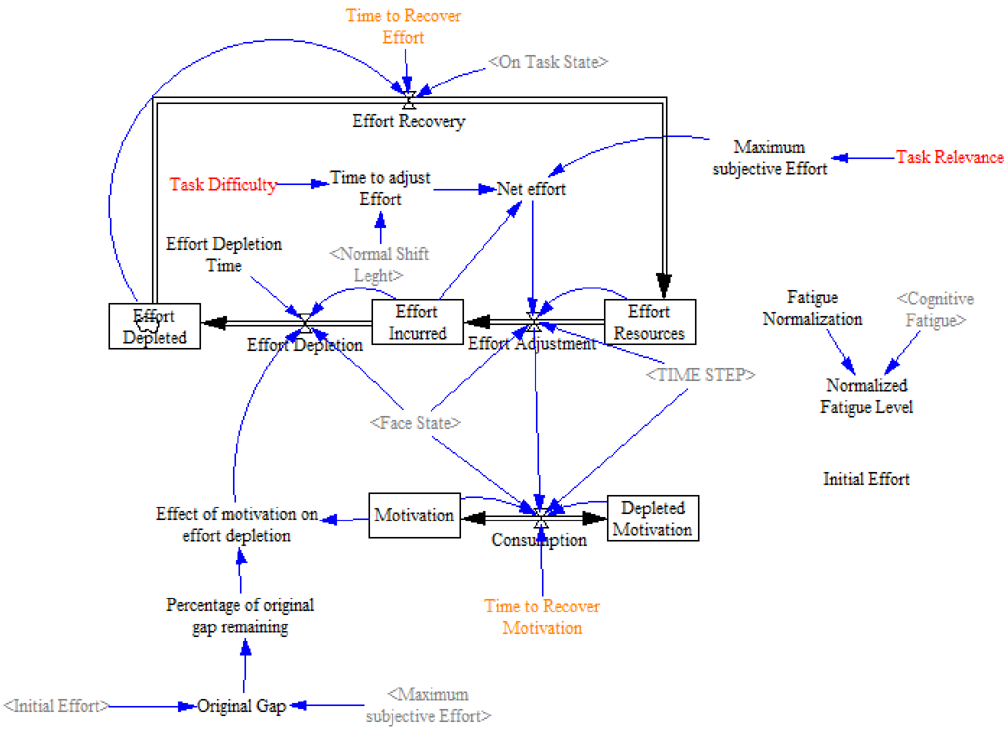

Figure 20. Effort Sector Stock and Flow Diagram

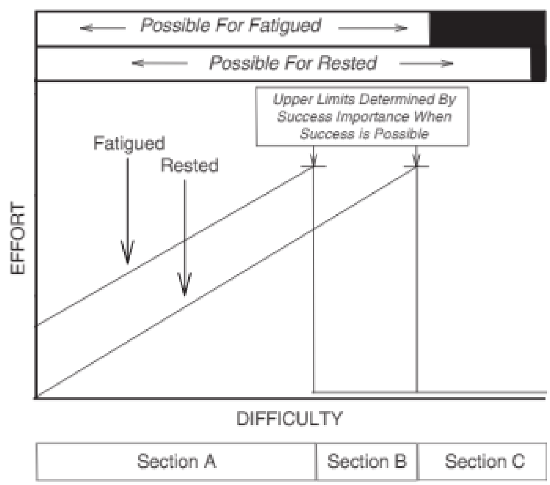

Figure 21. Challenge Difficulty and Effort for Fatigue and rested Individuals as shown in Stewart et al. 2009.

To translate the previous, into a system dynamics model, proxy values had to be used because of the "soft" characteristic of *effort* and *difficulty* variables. *Effort* uses as a proxy *cognitive fatigue* as its **initial level** (*initial effort*) depends on this variable. *Task difficulty* uses *normal shift length* (8 hours) under the assumption that in the best case scenario workers will maintain *effort* without suppression during the entire shift length. The minimum and maximum level for both was set in a range from 0 to 1, and the value of *cognitive fatigue* was normalized dividing by 100 as it covers a range of 0 to 100. *Effort depletion* stops *effort incurred* from being sustained. First, the *maximum possible effort* is determined by the "*task relevance*" (0 to 1). Second, as the *initial effort* depends on the cognitive fatigue level of the worker, the *normalized fatigue level* gives the value for *initial effort*.

Third, *maximum possible effort* minus *initial effort* determines the number of effort units that the worker is still able to incur, this value is divided by the number of hours the worker would sustain effort and this is how the *net effort* per period[2] (value on which level of effort incurred depends) is calculated. Fourth, a co-flow called "motivation" was used to activate *effort depletion* only when the distance between *maximum possible effort* and *effort incurred* has been covered or when no shift is being undergone by the worker. Fifth, *effort recovery* will happen whenever a worker is not on a shift or is under a break.

Maximum Level of Effort = Task Relevance

Net Effort = (Maximum Possible Effort - Effort Incurred) / Time to adjust Effort

Time to adjust Effort = IF THEN ELSE (Task Difficulty=0, TIME STEP/5.3,

*(Task Difficulty*Normal Shift Length)/5.3)*[3]

As highlighted before, motivation is also represented by a proxy. Its initial level is equal to the value between the maximum subjective effort and initial *cognitive fatigue* (effort worker is still able to incur), which is the same value used to determine the changes per period for *effort incurred*. The objective is motivation to reach zero when effort incurred reaches the *maximum possible effort level* and this activates the effort depletion. As the gap between *effort incurred* and *maximum possible effort* follows an exponential decay behavior, it will never be fully corrected (Sterman, 2000: 279), meaning that motivation as well will never reach exactly zero. For the previous reason, the depletion starts when 99.5% of the gap has been covered.

Original Gap =Task Relevance – Normalized Fatigue

*Percentage of the gap remaining = EXP (-5.3) *Original Gap*

4.4 Model Analysis and Base Runs

The objective of the model is to create a tool that can explain the effect of human cognitive factors and its suitability for prediction will be assessed. The model intends to be a generic model and the extent of it is limited by the availability of quantitative data for the representation of the factors affecting *cognitive fatigue and performance* and by the fact that the information required for enterprises to include must likely be already possessed by them. The more variables included in the model, the more difficult it would be for enterprises to obtain this data. The complexity of the model and detail would make the model less operational. For this reason, individual-specific factors, such as extroversion/introversion, caffeine consumption, alcohol consumption, usual sleep hours, have been omitted. In the following paragraphs, the causal loop diagram of the model will be described, a brief

[2] Net effort is equal to the effort adjustment per hour that acts as an inflow for effort incurred, makes effort incurred increase

[3] This formulation ensures an immediate suppression of effort based on task difficulty. Task difficulty defines how many hours, effort will be sustained (e.g. 100% = 8 hours, 50% = 4 hours), the division by 5.3 to ensures that 99.5% of the gap will be covered during the time specified. When task difficulty is 0, the task is perceived as impossible to achieve and no extra effort is justified, 99.5% of the effort gap should be covered immediately, the formulation TIME STEP/5.3 allows this to happen.

overview of the case study used to validate the results will be given. Followed by a description the results of validity tests performed. Finally, policy recommendations will be provided.

4.4.1 Causal Loop Diagram

A Causal Loop Diagram of the system was constructed, showing the dynamics of *cognitive fatigue* and performance. After the model was tested, it was concluded that it could not replicate the behavior for productivity accurately and two sectors were added to account for this limitation. In the following paragraphs, the description of each loop within each sector will be specified.

4.4.1.1 Cognitive Fatigue Sector

For the **Cognitive Fatigue Sector**, loops are described by factor (five factors are used to get the *cognitive fatigue* score based on the **Fatigue Index**). The description of the loops that form the model includes specific terms described in more detail in section Formulation of a Simulation Model4.3.

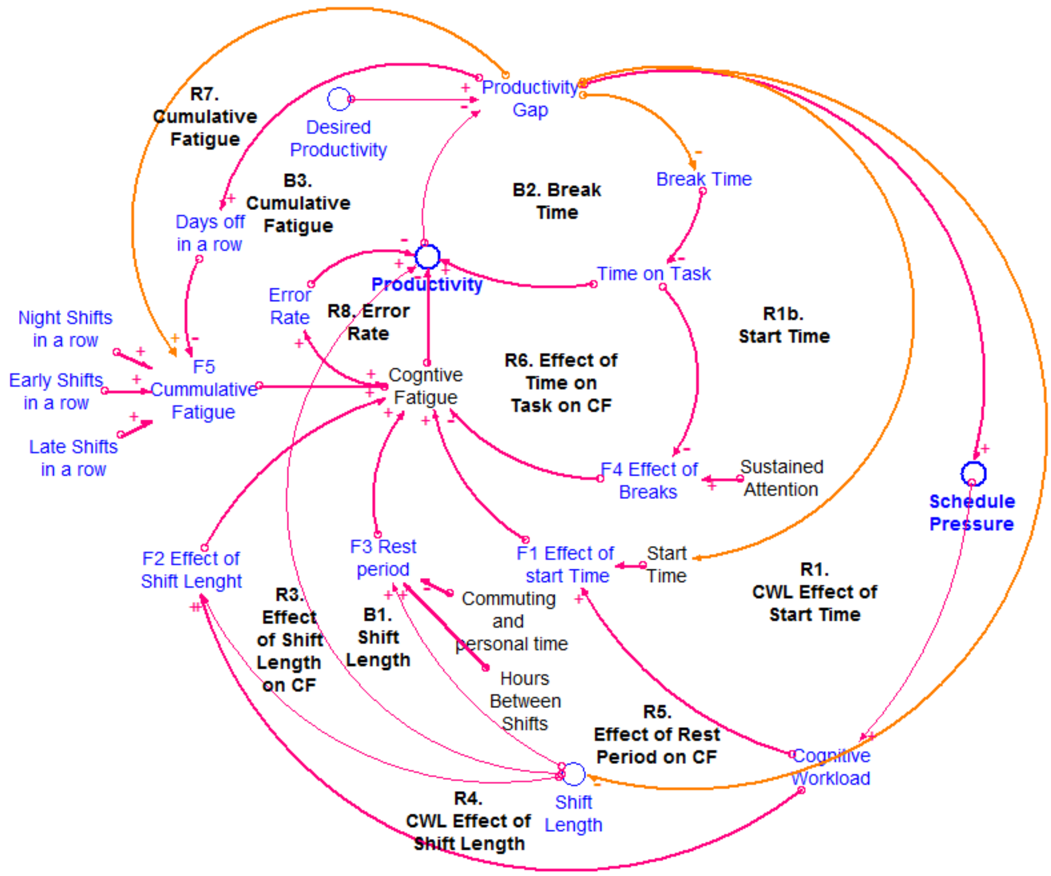

Figure 22. CLD Cognitive Workload, Fatigue and Productivity[4]

[4] Orange Lines represent how the state of the system affects decisions taken by the managerial team of the organization but that have to be specified for each shift in the model because these represent discrete events for shift schedules (shift start time, shift end time, break start time, break length and cumulative days in a row with the same schedule).

F1 Start Time

Loop R1b. Start Time

The time of the day in which a shift starts has an effect on the *cognitive fatigue* that individuals will develop over the day. this variation is given by circadian rhythms, which reflect the alertness levels individuals have at different times of the day and follow an oscillatory pattern. A lower score for shifts starting in the morning is assigned and this score increases for later shifts until a peak is reached in the evening (approximately at 18 hours) and then the score starts decreasing again. If a shift starts early in the morning or late in the afternoon the fatigue score will be higher, in comparison to a shift starting at different times. Managerial task design would decide the *shift start time* according to the amount of work to be done or the gap between the current state and the company's goals. A higher Fatigue Score will lead to lower productivity, increasing the number of early/late starts and increasing *cognitive fatigue*.

Loop R1. Cognitive Workload. Effect of Start Time on Cognitive Fatigue

Although the process provoked by circadian rhythms happens naturally, the amount of workload, individuals are engaged in varies. High levels of workload increase the contribution of shift *start time* to *cognitive fatigue (F1. Effect of start time)*. In a situation in which productivity is below the objective, individuals would be required to work at a stronger pace for reaching their objectives, generating schedule pressure on them and leading to higher *cognitive workload*, which increases the value of the *effect of start time* on *cognitive fatigue* in comparison to normal workload conditions. as *cognitive fatigue* increases, productivity decreases and generates higher *schedule pressure*.

F2 Shift Length

Loop B1 Effect of Shift Length on Productivity.

The distance from objectives affects the *shift length.* In a situation in which productivity is below the desired level (goal), managers may force workers to work longer hours with the objective of increasing productivity and decreasing the gap between the desired and the actual state. When productivity is closer to the desired level (goal) the shift length would be decreased to reach the normal amount of work hours (*normal shift length*).

Loop R3 Effect of Shift Length on Cognitive Fatigue.

The *Shift Length* also impacts *cognitive fatigue* ratings. In a situation in which productivity is below the objective/desired level, managers may ask the personnel to work longer hours with the objective of increasing *productivity*. This action will generate a higher level of *cognitive fatigue* compared to normal conditions (eight hours shifts). A higher level of *cognitive fatigue* will cause *productivity* to decline, increasing the *productivity gap* once more.

Loop R4 Cognitive Workload. Effect of Shift length.

The amount of *cognitive workload* also affects *cognitive fatigue* ratings. In a situation in which productivity is below the objective/desired level, individuals would be required to work at a faster work pace for reaching their objectives. This will generate *schedule pressure* on them and lead to higher *cognitive workload*. This increases 30% the fatigue contributions per unit of time in comparison to normal *workload* conditions. A higher level of *cognitive fatigue* generates lower *productivity* increasing the *productivity gap* and generating higher schedule pressure. The lower the *productivity* of an individual is in comparison to the *productivity goal* the higher the gap between these two values.

The bad implementation of a policy focusing on the extension of the *shift length* with the objective of increasing *productivity* can lead to a situation in the short term productivity is increased but as well an increment in *cognitive fatigue* is triggered. Leading in the long term to a lower level of *productivity* due to a higher level of *cognitive fatigue. Especially* when the worker is operating in a condition of high *cognitive workload* (due to high schedule pressure).

F3 Rest period

Loop R5 Effect of Rest Period on Cognitive Fatigue

A longer shift may affect the hours left for the worker to recover after a shift (*rest period*), increasing *cognitive fatigue* ratings. In a situation in which *productivity* is below the desired level, managers may ask the personnel to work longer hours with the objective of increasing *productivity*. This action will generate a shorter *rest period* that will lead to a higher level of *cognitive fatigue* in the next shift. This would depend on the final amount of hours of rest in comparison with the required hours according to the time of the day the rest period ends. A higher level of *cognitive fatigue* will cause *productivity* to decline, increasing the *productivity gap* once more. It is important to also consider *commuting and personal time* requirements when planning shifts for employees. As these factors also decrease the total rest period. A lack of consideration of them can lead to an oversight of unfavorable conditions for the workers leading to higher *cognitive fatigue* effects. Extending the shift length can have a third negative effect on fatigue, as the rest period of workers will also be affected.

F4 Effect of Breaks/ Time-on-task

Loop B2 Effect of Time-on-task on Cognitive Fatigue

In a situation in which *productivity* is below the goal, managers might intend to reduce the *amount or length of breaks* with the objective of increasing the time-on-task. A higher time-on-task will cause a higher *productivity* level.

Loop R6 Effect of Time-on-task on Cognitive Fatigue

In a situation in which *productivity* is below the goal, managers might intend to reduce the *amount or length of breaks* with the objective of increasing the time-on-task. This action will also generate a higher level of *cognitive fatigue* in conditions when the task requires sustained attention. A higher level of *cognitive fatigue* will cause *productivity* to decline, increasing the *productivity gap* once more. The detrimental effect can be even higher depending on the time of the day. In the afternoon and night times, less time-on-task and more breaks are necessary. It is important to consider the breaks duration. A minimum duration of fifteen minutes is needed to restore individual's cognitive levels.

F5 Cumulative Fatigue

Loop R7 Cumulative Fatigue

In a situation in which *productivity* is below goals, managers might intend to increase the number of *night, early or late shifts* the workers are engaged in during a continuous period of work. This action will also generate a higher level of *cumulative cognitive fatigue*. *Cumulative cognitive fatigue* cannot be restored even if the hours between shifts are sufficient. A higher level of *cumulative cognitive fatigue* will cause. higher *cognitive fatigue* at the beginning of a shift, causing a lower level of *productivity*. this effect will be further augmented during the shift as the other factors cause *short term cognitive fatigue* accumulation.

Loop B3 Cumulative Fatigue

The way in which *cumulative fatigue* can be decreased and a worker's cognitive capacities can be restored is by assigning *days off* in the worker's schedule. In a situation in which *productivity* is below the objective/desired level, managers might intend to decrease the number of continuous *days off*. This will in turn cause a higher level of *cognitive fatigue* at the beginning of the shift and a lower *productivity* increasing the gap to reach productivity goals.

Loop R9 Days off

It is important to note that the more days off a worker needs also affects *productivity* as the worker is not involved in its regular activities. A higher number of days off would also decrease productivity increasing the gap to reach productivity goals. More night, early or late shifts in a row cause a higher need for days off to restore cognitive capacities.

4.4.1.2 Manufacturing sector

Loop R8 Error Rate

An increment on *cognitive fatigue* caused by any of the previous factors mentioned causes a higher *error rate* as the worker is not able to perform his work with full cognitive resources. A *higher error rate* would cause lower *productivity*, producing a pressure to increase *time-on-task, shift length, (night, early and late) shif*ts in a row, and/or to decrease those factors that restore the worker's capacities such as *rest period* and *breaks*.

4.4.1.3 Model extension

The extension to the model contributed with two extra major loops. A **reinforcing loop R9** making *productivity* increase and **a balancing loop B11** making *cognitive fatigue* lower by increasing *productivity* due to *effort incurred* by the workers on the task. A detailed explanation is included below for each of the extra loops. Figure 23 shows the main loops of the cognitive fatigue sector and its interaction with the extra sectors. The loops added to this diagram are R9, R10, R12, B11, B12.

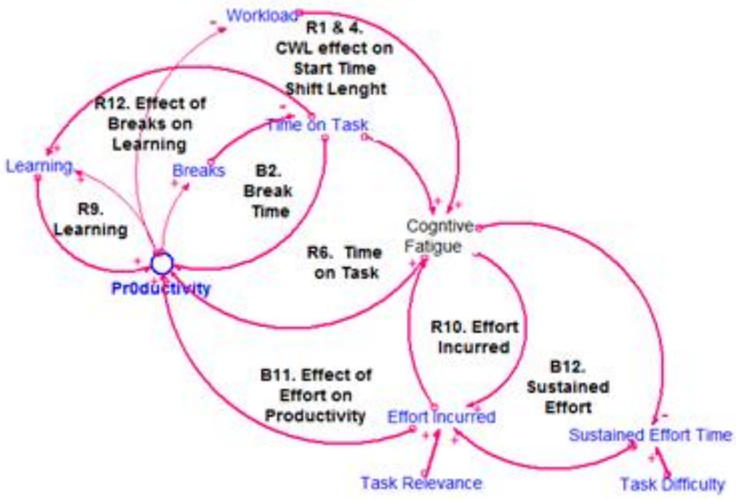

Figure 23. Extended Model Causal Loop Diagram

Learning Curve Sector

R9 Learning

Each product/order manufactured will increase the worker's *knowledge (learning)*. Resulting in a lower *production time per unit* and increasing *productivity*. With a higher level of *productivity* compared to what it would have otherwise been, a higher level of *knowledge (learning)* will be achieved.

R12 Effect of Time-on-task on Learning

As previously described, the level of *productivity* would be compared against the desired levels by managers in order to decide the amount and length of *break*s. A low *productivity* would then be translated in fewer breaks which would increase the time-on-task and increase the *learning* achieved as more units are produced. As the workers become more experienced this increases *productivity*. Nevertheless, it is also worth considering that increasing the time-on-task can have non-desired consequences, as highlighted by the **loop r6.** Time-on-task, increasing the amount of *cognitive fatigue* and diminishing *productivity*.

Effort Sector

R10. Effort Incurred

The level of *cognitive fatigue* determines the level of *effort incurred* by the worker. A higher level of *cognitive fatigue* will result in a need for higher *effort incurred*, as higher energetic demands exist for a fatigued worker in comparison with those of a rested employee. This, in turn, will be translated into higher levels of *cognitive fatigue*, as the more *effort* the worker puts in the task the more *fatigued* he gets. *Task relevance* acts as a moderator defining the maximum possible level of *effort* in a scale from zero to one.

B12 Sustained Effort

High levels of *cognitive fatigue* affect negatively the amount of time in which effort increments will be sustained (*sustained effort time*), translating into a lower overall *effort incurred* and lower *cognitive fatigue*.

B11. Effect of Effort on productivity

The more *effort incurred*, the more *productivity* a worker will have, the more *productivity*, the more *breaks*, the less time-on-task and the less *cognitive fatigue*, causing the possibility of a longer time of sustained effort increments during the next shift. Nevertheless, **loops r9 and b2** also intervene, increasing even more, the productivity due to the learning effect and due to an increment on time-on-task.

4.4.2 Case study

The case study used to verify the results of the model was provided by the Netherlands Organization for applied scientific research TNO. It was performed at Vanderlande Industries and aimed to study sustained performance in order picking after the introduction of a new workstation to diminish health risks (Bosch, De Looze, & Ten Hoor, 2008). The authors highlight that order picking refers to the process of retrieving products from storage locations according to orders issued by customers. Large volumes of items have to be picked per unit of time, causing high *cognitive workload* to operators and possibly leading to performance impairments or health risks. To measure *cognitive workload*, the Perceived Mental Exertion (BSMI) scale was used in the case study and both orders and products picked were recorded per minute and averaged each 15 minutes (The results of the model follow the same pattern).

The participants of the case study were required to apply their maximal acceptable work pace during the first 15 minutes (considered as high mental workload for the model runs), operators were then required to continue working for 105 more minutes, followed by a 15 minutes break and a second 105 minutes' work period. When this was done, operators were asked to continue working for 10 more minutes at a pace that could be sustained for 8 hours. Nevertheless, the results obtained from this part was not used for the model validation.

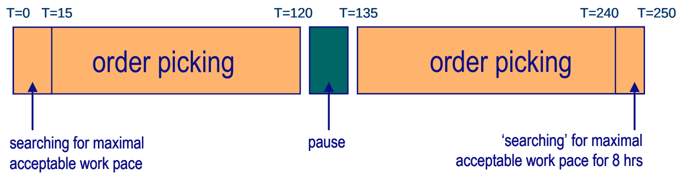

Figure 24. Task design for case study

Source: (Bosch et al., 2008)

4.4.3 Model Validation

To increase confidence in System Dynamics models several tests can be done for model validation. Senge and Forrester (1980) identified 17 tests that can be used for performing the previous. These tests focus on validation of the model structure, model behavior and the policy implications. The previously mentioned authors also recognized that the number of available tests is high and not all of them are relevant for all modeling applications. Due to this fact, they identified some of them as "core tests". The tests performed in this work were selected using the previous classification. All the tests of the model structure were performed and three tests of model behavior were included (behavior reproduction, behavior anomaly and behavior sensitivity). The tests of policy implications were omitted as policy implementation wasn't within the boundaries of the project.

Tests of model structure

1. Structure Verification and Parameter Verification.

The structure and parameters contained in the model for calculating *cognitive fatigue* were obtained from a bio-mathematical model **Fatigue Index**. This index was developed using data from both theoretical and empirical sources (laboratory experiments, field trials, a shift work study, objective data collection, literature review, questionnaire study). It was tested against an existing alertness model and a symposium was created to obtain expert opinion. Only three additions were made to the model that weren't considered by the original index. The first one was adding a stock labeled *attentional resources* with the only purpose to represent the time-on-task and increment on fatigue if a break is not taken when necessary. In other words, the sole objective was to create the adequate effect of time-on-task on fatigue, which was also compared against literature (refer to section 4.3.1 for a more detailed description).

Fatigue Recovery was added to the original model. The **Fatigue Index** gives a fatigue score for operators at the end of the day but it does not follow the development of fatigue throughout the day, in the index "shift related fatigue" is accumulated throughout the day and then depleted at the end of the shift. Nevertheless, to fit real-world behavior (case study data and literature) a depletion of fatigue whenever an operator was not working had to be included. This, however, posed the beginning of a new uncertainty, requiring further revision on the parameter value. There was no agreement between data coming from different sources. For the purpose of this work, the adjustment time used for depletion was calculated using data from the case study. A group model building session was held for expert judgment of the model in which both causal loop diagrams and the Stock and Flow Model were presented to verify structure and parameters. The feedback was positive and the only correction was in relation to clarification of the definition of "Attentional Resources" as the term can suggest different meanings for different audiences.

The two extra sectors added to the **Fatigue Index** were based entirely on literature and adapted to fit a System Dynamics Model structure. Structure and parameters from the manufacturing sector were based on the generic structures proposed by Eberlein and Hines (1996) as no relevant data was found during the literature review and no sufficient information could be obtained from the case study. Structure and parameters for the **Effort Sector** were defined according to literature, based entirely on the work of (Stewart et al., 2009; Stewart et al., 2006). Structure and parameters for the **Learning Curve Sector** were defined according to literature, using the part of the model proposed from (Givi et al., 2015a).

2. Extreme Conditions Test

For performing an extreme conditions test, each rate equation must be traced back to the level they are dependent upon (Forrester & Senge, 1980). Once these levels are identified, their values must be altered using extreme values (minus infinity, zero, plus infinity). The authors mention that these tests are effective to identify flaws in the model structure and to identify whether the system performs well even under extraordinary circumstances. Four of the levels in the model are protected by a maximum and minimum value. The extreme condition test for these levels was made by altering their rates and inserting instead extreme values to test that minimum or maximum limits weren't surpassed. The levels on which rates are dependent upon are listed in Table 9 per sector, in the following paragraphs a brief overview of the tests done will be given, for further detail please refer to Annex 4. Validity Tests.

Inflow	Levels/Sublevels	Outflow	Biflow	Sector	Dependent Rate/Level	Max	Min
Fatigue Increment	Cognitive fatigue (ST)	Fatigue Recovery (ND)		Cognitive fatigue	Effort; Effort,CognItive Fatigue ST, Knowledge --> Productivity--> Workload --> Cognitive Fatigue	100	0
Attention Utilization Rate	Attentional Resources	Attention Utilization Rate (ND)	x	Cognitive fatigue	Completition Rate* via Schedule Pressure--> Breaks--> Attentional Resources	1	0
Effort Adjustment	Effort Incurred	Effort Depletion (ND)		Effort	Cognitive Fatigue	1	0
Consumption	Motivation	Consumption (ND)	x	Effort	Effort Adjustment --> Cognitive Fatigue	1	0
Learning	Knowledge	Forgetting (ND)		Learning Curve	Accomplishing Correctly --> Cognitive Fatigue	Infinity	0
Start Rate (ND)	Work in Process Inventory	Completion Rate		Manufacturing	Effort, Cognitive Fatigue, Knowledge --> Productivity	Infinity	0
Accomplishing Correctly	Correct Work			Manufacturing	Cognitive Fatigue; Effort, Cognitive Fatigue, Knowledge --> Productivity	Infinity	0
Accomplishing Incorrectly	Undiscovered Rework	Discovering Rework (ND)		Manufacturing	Cognitive Fatigue; Effort, Cognitiveve Fatigue, Knowledge --> Productivity	Infinity	0

Table 9. Levels, Rate Equations and dependencies[5]

[5] ND means no dependency. For some stocks, either the inflow or outflow doesn't depend of other levels within the system. One example of this is "forgetting" a fixed forgetting rate exists and for any scenario it will remain the same.
Schedule pressure is represented in the system as "mental workload" and gets activated when the "desired completion rate" is higher than the "average completion rate" activating a higher accumulation of cognitive fatigue. This structure is contained in the model, nevertheless it is not activated as no information was provided for this for the case study.
The managerial decision of changing the shift length, length of breaks is not represented in the system as for it to calculate the cognitive fatigue levels requires the detailed time for the start of shift, end of shift, exact break times and break length and this decisions can't be represnted in a System Dynamics model.

For the **cognitive fatigue sector**, detailed tests were performed on the level *cognitive fatigue (ST)* as it has an influence on the **effort sector** and the **manufacturing sector**. The effect of the changes made on these level on both sectors was also assessed. For the level attentional resources, it was only assessed whether the stock stayed within the maximum and minimum values when altering the rate equations. The behavior of the system when altering the values of both levels, showing no abnormalities under extreme values and the maximum and minimum limits were respected.

For the **effort sector**, detailed tests were performed on the level *effort incurred* as it has an influence on the **cognitive fatigue sector** and the **manufacturing sector**. The effect of the changes made on these level on both sectors was also assessed. For the level *motivation*, it was only assessed whether the stock stayed within the maximum and minimum values when altering the rate equations. The behavior of the system when altering the values of both levels was as expected, showing no abnormalities under extreme values and the maximum and minimum limits were respected.

For the **learning sector**, detailed tests were performed on the level *knowledge*, as it is the only level of the sector. This level has an influence on the **manufacturing sector**. The effects on the **manufacturing sector** of the changes made were also assessed. The behavior of the system when altering the values of the levels was as expected, showing no abnormalities under extreme values and the minimum limit was respected.

The final sector tested was the **manufacturing sector**, the extreme condition tests were performed on the level *work in process inventory, correct work and undiscovered rework*. As the three previous sectors had effects on this last one, the tests had already been partially completed. Due to this fact the tests performed, were not as detailed as for the previous sectors. After the tests were concluded it was noted that the behavior of the system when altering the values of the levels in the manufacturing system was as expected, showing no abnormalities under extreme values and the minimum limit was respected.

3. Boundary Adequacy

The boundary adequacy within the model was done via a Bull's Eye Diagram. Those variables that are calculated by the model were placed in the "Endogenous" section, those values that have to be indicated are listed in the "Exogenous" section and those that were not included in the "Excluded" section. The aim of the model guided the boundary selection, as the purpose was to generate a general structure that could describe a how cognitive factors affect *productivity* within a manufacturing setting. The more general a model is, the less detail it will include, as its structure must be designed to fit multiple situations; on the other hand, a higher amount of detail would be translated into higher data requirements, putting at risk the usability of the model. More emphasis must be put on the operational representation of the system (Sterman, 2000: 81).

The model had a single task focus; It doesn't consider individual factors such as extroversion, general cognitive ability, age, work ethic; Physical elements of the work environment such as noise level, air temperature, are not included; Organizational environment factors such as task switching, distractions, communication, training are not included. (Baines, Asch, Hadfield, Mason, Fletcher, & Kay, 2005).

For factors 1 and 2 the fatigue rating is higher when mental workload is presented. The structure of the model allows treating this variable as either exogenous (as a switch for whenever high *mental workload* exists) or as endogenous (when information about the desired production rate exists). Nevertheless, no distinction is made for activities requiring (high, medium or low) mental workload, this addition to the model could result in a higher detail.

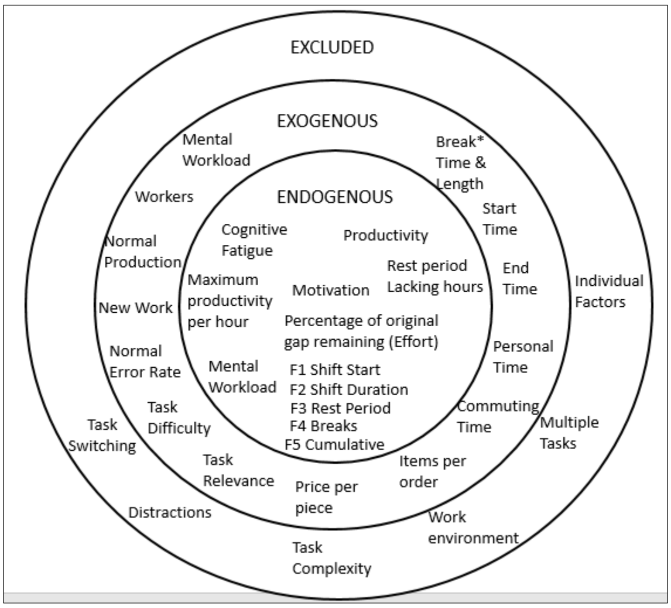

Figure 25. Bull's Eye Diagram. Boundary Adequacy Test

4. Dimensional Consistency

The dimensional consistency was checked during the model creation and after the finalization of it using the tool included in Vensim. The only errors that remain are caused by using dimensioned variables as input for non-linear functions. Nevertheless, the rest of the auxiliaries, levels, rates and constants show dimensional consistency.

Tests of model behavior

Behavior tests before model expansion

The behavior generated by the model is represented by the variables *cognitive fatigue* and p*roductivity per minute*. The fit of the model results of these variables was tested against data from a case study provided by TNO. The case study is related to sustained performance and workload in order picking (Bosch et al., 2008). The fatigue scale for both sets of data differed, the **Fatigue Index** provides a score between 0 and 100. Whereas the case study used the BSMI scale (Rating Scale Mental Effort), providing a score between 0 and 150. To make both scales comparable the results given by the SD model were multiplied by 1.5. Even before performing statistical tests to the model. After testing the model (cognitive fatigue sector and manufacturing sector), it could be observed that the fit between the two sets of data was not optimal (Figure 26 and Figure 27). The model reached for *cognitive fatigue* a maximum figure of 8.59 BSMI, while the case study reached a maximum of 25.63 BSMI. In the case of the variable *productivity*, it was evident that not only the numbers differed but also the trend.

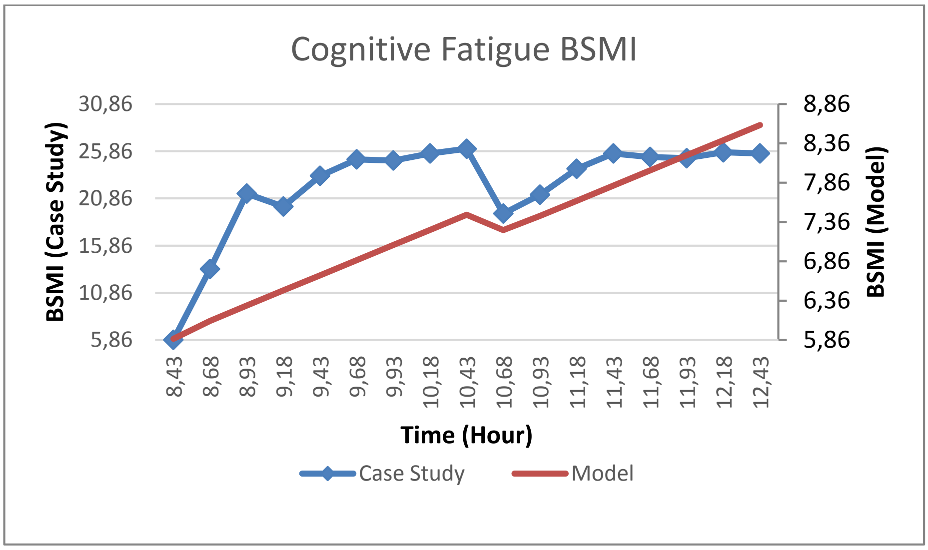

Figure 26 Fit of the model to data. Cognitive Fatigue Base Run

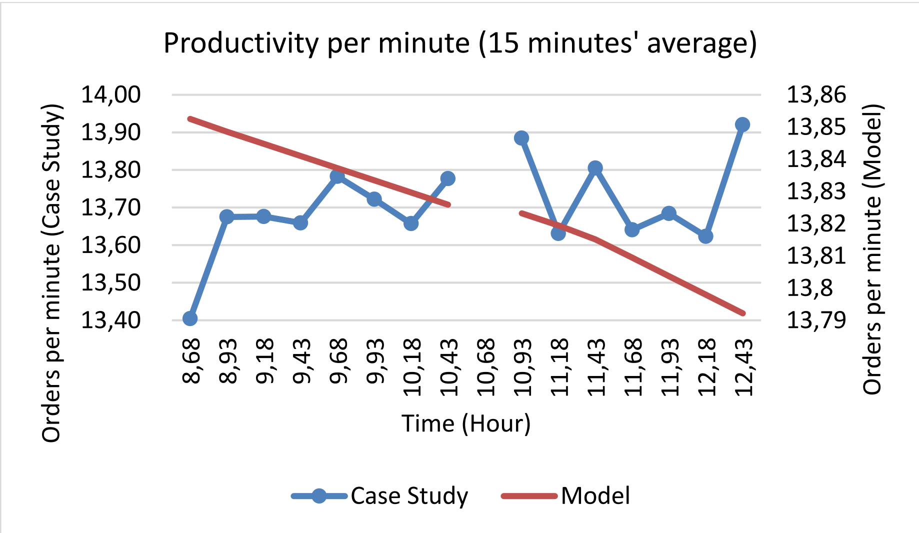

Figure 27. Fit of the model to data. Productivity (15 minutes' average) Base Run

Behavior tests after model expansion

With the purpose of explaining the behavior showed for performance in the case study two sectors were added to the model. The model was built under the statement that the higher *cognitive fatigue* is, the lower *productivity* per unit of time will be. Nevertheless, the data from the case study showed differently, even if *cognitive fatigue* increased over time, *productivity* decreased. The inclusion of a loop that would increase *Productivity* was needed. Based on data from the literature review and a Group Model Building Session for model structure verification. It was concluded that two explanations for the increment of productivity could be given (1) by learning, the more a worker learns, the higher productivity he will have and (2) by effort, the more effort a worker puts on the task the higher the productivity will be. Learning by itself could not explain the behavior, as performance didn't increase continuously. Effort was chosen, as it is an element included in several frameworks (e.g. Effort-Rewards-Imbalance models and Resource-Control Theory) and can produce both increments and decrements in productivity during a shift. Likewise, Yeh and Wickens (1984) studied the dissociation between subjective measures and objective workload measures. From their work it can be inferred that subjective workload measures cannot accurately be used to predict performance as subjects could increase the amounts of resource investments (*effort incurred*) in order to prevent performance decrements. Meaning that even if *mental workload* is high or high levels of *cognitive fatigue* exist, performance could not be altered as worker's could incur effort to avoid performance impairments.

The results show that the **Cognitive Fatigue sector** was not impacted considerably, effort only creates an increment on the *Fatigue increment* per period of time but the structure and parameters were kept as the original **Fatigue Index**. The overall model results for the **Extended Model Run** didn't differ considerably from the **Base Run**. Nevertheless, the results for *productivity* showed a significant improvement.

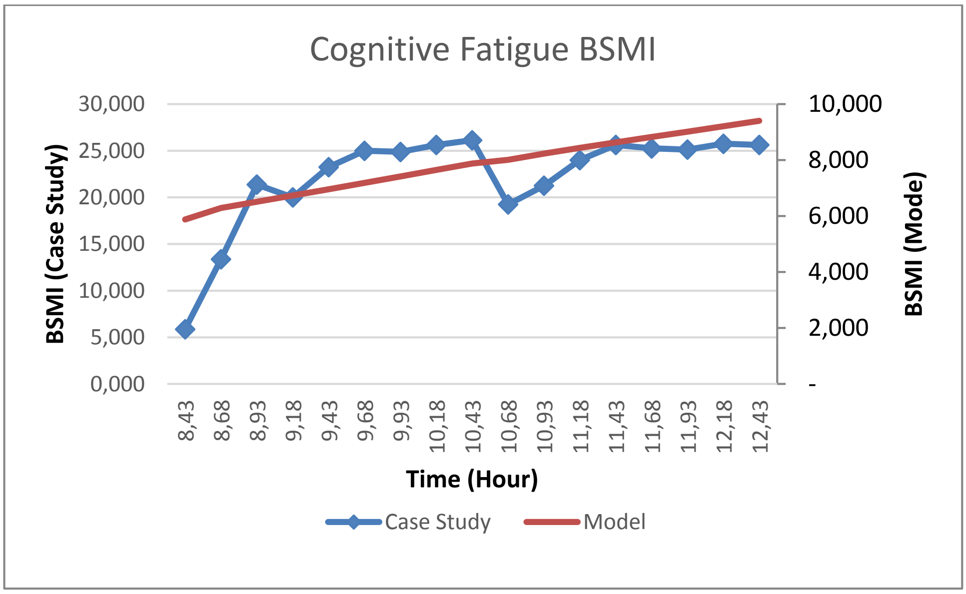

Figure 28. Fit of the model to data. Cognitive fatigue extended Model

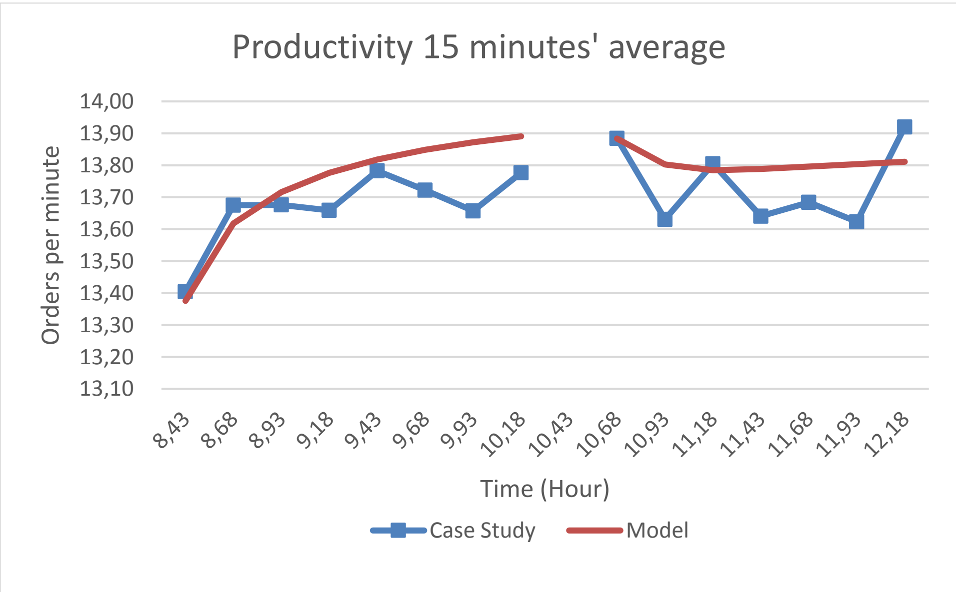

Figure 29. Fit of the model to data. Productivity (15 minutes' average) Extended Model

Finally, the Vensim optimization tool was used to determine if the current model, with different parameters could give a better result for the prediction of *cognitive fatigue*. The values for the variables: *effort impact, fatigue depletion, effect of mental workload on f1 and effect of mental workload on f2* were altered as they are the parameters with a higher effect on the *cognitive fatigue* value computation. The results showed that the structure of the model can produce the desired behavior, but the parameters would need to be adapted. A search was done with the purpose of finding new values in the literature that could be used to justify the results shown by the optimization, nevertheless, no relevant information was found and it was concluded that this information would need to be collected empirically as the values found in literature for the variables differ significantly from source to source.

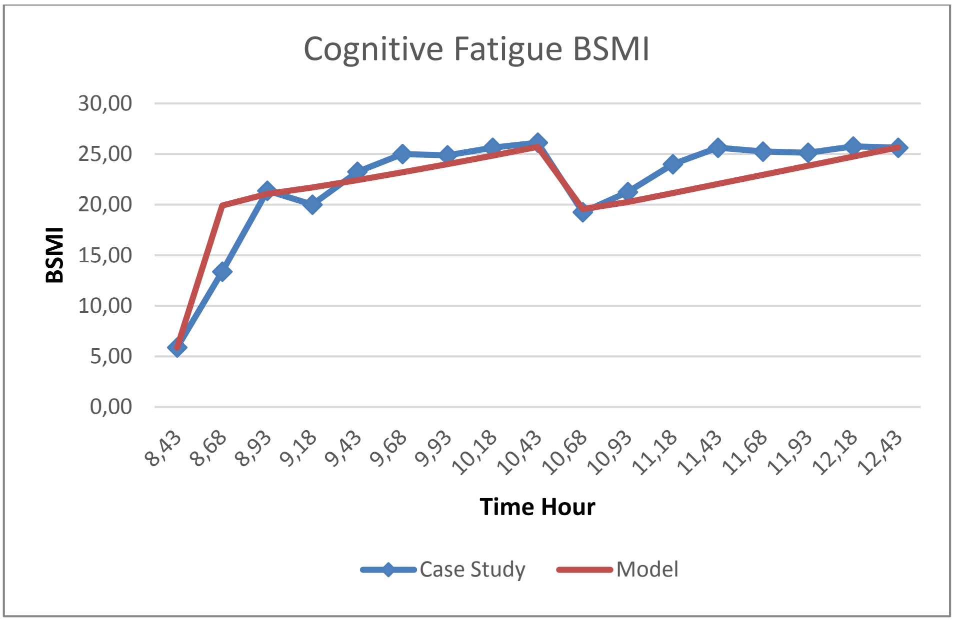

Figure 30. Fit of the model to data. Cognitive Fatigue Base Run Extended Model Modified Parameters

The behavior reproduction tests were done for the three different models: (1) Base model (**Cognitive Fatigue Sector and Manufacturing sector**), (2) Extended model (Including **Effort Sector** and **Learning Curve Sector**), (3) Parameters change based on Vensim optimization tool.

5. Behavior reproduction test

As suggested by Sterman (2000: 874-870) Theil inequality statistics were used to determine the statistical fit between the two sets of data, as they provide insight not only on the size of the error between data but also on the error sources. Knowing the error sources can prove to be beneficial for determining if the error is due to systematic or unsystematic components.

Statistics	Cognitive Fatigue	Productivity
Mean Model	7.39	13.82
Mean Case Study	22.20	13.70
Standard Deviation Model	0.87	0.02
Standard Deviation Case Study	5.20	0.12
Mean Square Error	240.77	0.03
Pearson's correlation	0.71	-0.43
Um	0.91	0.48
Us	0.08	0.33
Uc	0.01	0.19
Um+Us+Uc	**1.00**	**1.00**

Table 10 Theil Statistics. Base Model Run

Um coefficient refers to the fraction of Mean Square Error (MSE) originated due to bias. In this case, for bot*h cognitive fatigue* and *productivity,* the biggest part of the mean square error can be explained by bias. Meaning that a systematic error should be corrected in the system by parameter adjustment. **Us coefficien**t refers to the fraction of the error that is due to unequal variation. In the case of *cognitive fatigue,* this value corresponds to less than 10% of the mse but instead for productivity the value accounts for more than 30% of the MSE. **Us coefficient** value is high when the trend between the model and reference data differ; when fluctuations exist within a system, the value of this coefficient indicates fluctuations with the same phase but different amplitude; and only if cycles and noise are relevant for that specific case, a number close to one would indicate that a systematic error exists. In the case of *productivity*, it is evident that the high value of the **Uc coefficient** indicates a systematic error due to the trend. Finally, **Uc coefficient** reflects an unequal covariation, and can represent a phase shift in data with fluctuations or the model having the same mean and trends but differing from point-by-point data. This type of error only is relevant if the purpose of the study is related to cycles in data. The **Uc Coefficient** for *cognitive fatigue* is not significant but for **productivity** it constitutes almost 20% of the error, meaning that the model differs from point-by-point data.

Based on the previous analysis it can be concluded that a systematic error exists in the model for the calculation of both *cognitive fatigue* and *productivity*. The discrepancies in the results for the cognitive fatigue variable could arise from several factors: a) differences in measures between scale values b) face validity of subjective scales, the measurements could not measure what was intended to be measured. (Roach, 2006) c) possible need for adaptation of the **Fatigue Index** calculation to the specific situation (order picking, manufacturing sector). The **Cognitive Fatigue sector** in the SD models relies entirely on information provided by the **Fatigue Index**, the **Fatigue Index** would give a similar result compared to the one given by the model (low values in comparison to those reported by the participants in the case study).

In the case of productivity, it is clear that the actual structure of the model could not replicate the results and enhancements needed to be done to achieve the same trend within the two sets of data. With this purpose, two extra sectors were included in the model "**Effort Sector**" and "**Learning Curve Sector**". These sectors were included based on the results of a Group Model Building session held for validation of the **Fatigue Index**, on the Performance Shaping Factors framework and the theories presented in the theoretical background of this work.

The Theil statistics for the new version of the model, don't change much for the ***Cognitive Fatigue Sector*** a high Mean Square Error and systematic error can still be observed. Nevertheless, for the statistic for productivity show more favorable results. The mean square Error diminished, a positive correlation can now be observed and the error due to bias (Um) decreased considerably. Us reached a number closer to zero, meaning that the trend of the simulation and the data from the case study is the same. The main origin of the mean square error is now due to an unequal covariation (Uc). Meaning that the model fluctuates with the same mean, amplitude and frequency of the data but with a slight phase shift.

the pearson's correlation coefficient (.70) for both *cognitive fatigue* and *productivity* confirm the statistical significance of the model.

Statistics	Cognitive Fatigue	Productivity
Mean Model	7.78	13.77
Mean Case Study	22.20	13.70
Standard Deviation Model	1.04	0.12
Standard Deviation Case Study	5.20	0.12
Mean Square Error	228.46	0.01
Pearson's correlation	0.70	0.70
Um	0.91	0.35
Us	0.08	0.00
Uc	0.01	0.64
Um+Us+Uc	**1.00**	**1.00**

Table 11. Theil Statistics. Effort and Learning Curve Sector included

Finally, with the purpose of verifying the structure for *cognitive fatigue*, as indicated before, a change in the parameters was done using the optimization tool incorporated in the vensim software package. The mean square error in the case of *cognitive fatigue* diminished and the error due to bias was now minimal (0.05). The correlation coefficient increased from .70 to .92 for *cognitive fatigue*, showing an increment in significance for the model.

Statistics	Cognitive Fatigue	Productivity
Mean Model	21.70	13.74
Mean Case Study	22.20	13.70
Standard Deviation Model	4.38	0.15
Standard Deviation Case Study	5.20	0.12
Mean Square Error	4.77	0.02
Pearson's correlation	0.92	0.55
Um	0.05	0.09
Us	0.14	0.05
Uc	0.81	0.86
Um+Us+Uc	**1.00**	**1.00**

Table 12. Theil Statistics. Effort and Learning Curve Sector included with altered parameters.

6. Behavior Anomaly (Loop Knockout Analysis)

The behavior anomaly test is done to verify that not behavioral anomaly is found within the model that would suggest flaws in model assumptions (Senge & Forrester, 1980). A common method for performing the test is by performing loop knockout, which aims at eliminating loops, it is also helpful for determining the importance of a loop (Sterman, 2000). Only major loops were tested, meaning that the tests focused on those loops that have an effect on other sectors of the model. The first sector tested was the **cognitive fatigue sector**. Loops**: B2. Break Time, R6. Effect of Time-on-task on CF** and **R10. Effort Incurred** were knocked out. No anomalies were found in the behavior showed by the analysis. Nevertheless, after the loops were knocked out, the variation of the variable *productivity* was smaller. Meaning that loops B2, R6 and R10 are less strong than those included in the effort sector. The second sector tested was the effort sector. The loops**: B11. Effect of Effort on Productivity** and **R10. Effort Incurred** were knocked out The effects were as expected, the value for both *cognitive fatigue* and *productivity per minute* were lower in comparison to the base run as *effort incurred* had a minimal variation during the run due to the loop knockout, no anomalies were presented and the importance of the loop was justified. Finally, the learning curve sector was tested. For this sector only loop **R9. Learning** was knocked out, as it is the only relevant loop in this sector. The results showed that there is no short-term effect on the values of *cognitive fatigue* by knocking out this loop but the contrary happens for *productivity*. The value of *productivity per minute* diminishes considerably, proving no behavior anomalies and the importance of the loop.

7. Behavior Sensitivity

Univariate sensitivity Testing

Sensitivity testing was performed using the Sensitivity Analysis feature included within the Vensim DSS Software. The multivariate sampling method was selected (default sampling method) and a random uniform distribution was chosen. The aim of the sensitivity analysis is to show how exogenous parameters can affect the main variables used for testing the model, which are *cognitive fatigue* and *productivity per minute*. In order to achieve the previous, four tests were performed. The variables selected for the tests were those for which a higher degree of uncertainty exists due to lack of availability of information for their representation and/or they correspond to the sectors added to the model. These variables were: time to recover fatigue, effort impact, task difficulty and task importance. The results showed the possible range of values and behaviors, that can be produced by using altering the values selected for these variables. No anomalies in the behavior patterns were detected and the sensitivity was only numerical. Meaning that if the values of the selected variables change within the given range (selected according to each variable) different values for the variables *cognitive fatigue* and *productivity* will be produced by the model but the behavior will be as expected.

Finally, the model wasn't constructed with the aim to generate policies for a certain situation but rather to find the causalities behind changes in performance in a manufacturing setting caused by human cognitive factors. For this reason, only potential policies are mentioned in the text of this work but no inclusion was done in the model. As a result of the previous, no tests of policy implications were performed.

4.4.4 Conclusion

This section had the objective of describing the System Dynamics model and performing the relevant tests to ensure validity. *Cognitive fatigue* and its influence on productivity was modeled. Two extra sectors had to be added to the original model to explain this relationship better. *Cognitive fatigue* could not explain by itself the productivity behavior. Three models, *cognitive fatigue* (previously quantified), learning curve (previously quantified) and effort (adapted from an empirically tested theory) were integrated with a manufacturing setting model to account for the variations of productivity. The model shows an increment of productivity created by the effect of knowledge gained from experience, an increment/decrement in effort increasing/decreasing productivity according to task characteristics (task difficulty, task importance) and the effect of task design (work schedule), task characteristics (sustained attention, mental workload), homeostatic and circadian factors (time, sleep factors) on *cognitive fatigue* and how this affects productivity.

The benefit of the model and the use of System Dynamics is that nonlinearities and soft variables can be represented and it allows managers to understand the dynamics behind the behavior encountered (Barlas, 1996). The **Fatigue Index** only provides managers with a value for the end of a shift, with the System Dynamics model the development within a shift can be seen and how factors interact together can be understood better. A second advantage is the possibility that System Dynamics provides for merging data from different sources into sub-models, as shown by the use of different already quantified models in this work.

This model combines elements from Cognitive Load Theory portrayed by the homeostatic and circadian factors, from the effort-reward-imbalance model by including the concept of effort and task relevance. From arousal theory (Smit et al., 2003), the effect of sustained attention on performance , underload and overload theories are by considering resources as limited (attention and effort) and executive control from the merged theories, the individual can decide whether or not to continue incurring effort.

The simulation model is partially able to reproduce the reference mode with high levels of significance for productivity but not for *cognitive fatigue*. Nevertheless, it was shown that the structure for this sector could replicate the behavior by altering the value of some parameters. The exact values needed to replicate the behavior were not found on literature as conflicting information was encountered. The results show that a generic model of cognitive factors based on the fatigue risk index is not able to predict productivity by itself. A limitation of this work was the lack of possibility of obtaining empirical data as the case study had already been conducted and no access to the participants of the company was possible. A sector specific model and empirical data collection are suggested to obtain better results.

8. Policy Recommendations

This section focuses on describing policy recommendations that could be used to minimize the effect of human cognitive factors on performance. The policy recommendations will be divided into two parts: The first part will cover the time elements that comprise the time elements included in the **Fatigue Index**. This part will highlight the scenarios that could lead to minimize the *cognitive fatigue* score. These policies were created by the knowledge obtained from analyzing the information provided in the documentation of the **Fatigue Index**. The second part will focus on the whole system and will cover the four sectors of the model: **cognitive fatigue sector, effort sector, learning curve sector and manufacturing sector**.

As indicated before **task characteristics** are factors proper of the task, which cannot be changed by managerial decisions (e.g. an activity that requires sustained attention will have the same characteristics no matter which managerial decisions are taken). The part that can be manipulated is the **task design**, managers take decisions based on the company's goals. The policy recommendations that will be highlighted in the following paragraphs focus on the *task design*.

8.1 How to minimize the Fatigue Score provided by the Fatigue Index (Time related factors)

The policies highlighted in this section were not created as a result of the construction of the model. They are derived from the analysis done of the **Fatigue Index** for constructing the System Dynamics model. Nevertheless, it seemed relevant to be included in this work as after reviewing the documentation of both the Fatigue Risk Index (Spencer et al., 2006) and the Fatigue Index, no such information was found. The measures highlighted in this section are only a summary of the information used to construct the **Fatigue Index**, converted into a prescriptive notation. An example of the previous is the information provided in Table 14 where the maximum time between breaks according to the period of the day is specified.

1. ***F1 shift start***. For a weaker effect of **loop R1b**, shifts starting between 8:00 and 15:00 hours are beneficial, as they provide a lower fatigue rating as compared with those starting between 16:00 to 7:00 hours (please refer to Table 3). High levels of *mental workload* through the whole shift can increase the contribution of this factor by 4 units. It is especially important for tasks requiring high levels of *cognitive workload* to be scheduled strategically in times that provide a lower *cognitive fatigue score*. The previous would be to make **loop r1** weaker, in order to achieve a lower score for the **Fatigue Index factor 1**, and as a consequence to increase *productivity* and diminish the *error rate*.
2. ***F2 Shift Length***. One of the most apparent measures for diminishing *cognitive fatigue* scores throughout a shift is by controlling the *shift length.* Shifts of maximum 8 hours avoid the addition of extra fatigue units for factor F2. Nevertheless, understanding the mechanics behind the **Fatigue Index** can help in designing a better schedule, as not only the *shift length* is relevant for minimizing the *cognitive fatigue* score, but also the mixture of *shift length* and *start time* is relevant. For example, a 12 hours shift starting at 09:00 hours can be better handled by operators (resulting on 2/100 extra fatigue units per day) in comparison to a shift of the same length starting at 19:00 hours (resulting in 10/100 extra fatigue units per day) (please refer to Table 4). As the *shift length* diminishes, both **loop R3** and **loop R4** (when high workload is presented) are made weaker and lead to a lower score for the **Fatigue Index**

factor 2, increasing *productivity* and diminishing the *error rate*. The previous is especially relevant after an operator has been engaged on sequential late, night or early shifts (high initial *cognitive fatigue* score for the shift) or when an operator is engaged in activities with high *mental workload* (the fatigue score according to shift length is increased by 30%) and sustained attention requirements (factor 4 is activated).

3. ***F3 Rest Periods***. For avoiding high *cognitive fatigue* scores due to a lack of adequate *rest time* between shifts, managers must ensure giving workers a proper *rest period*, according to the shifts characteristics. For rest periods ending between 04:00 and 18:00 providing 13 hours is enough; for rest periods ending at 19:00 hours 15 hours are necessary; 17 hours for rest periods ending at 20:00; 19 hours for rest periods ending at 21:00 and finally, 20 hours for rest periods ending between 22:00 to 03:00 hours. This process will help to make **loop R5** weaker and will result in a lower score for the **Fatigue Index Factor 3**, increasing *productivity* and diminishing the *error rate*.

Rest Period End	Rest Period Length
04:00 - 19:00	13 hours
19:00 - 20:00	15 hours
20:00 - 21:00	17 hours
21:00 - 22:00	19 hours
22:00 - 04:00	20 hours

Table 13. Rest Period Length according to Rest Period End Time

4. ***F4 Breaks***. Both *break length* and break frequency have a considerable impact on *cognitive fatigue* when a worker is engaged in an activity that requires sustained attention. The minimum break length recommended by the **Fatigue Index** is 15 minutes and the frequency of breaks differ according to the time of the day. When the Frequency of Breaks is designed according to the period of the day, **loop R6** would not be activated, meaning that there would be no addition to fatigue by the **Fatigue Index Factor 4**.

Period	Time	Frequency of Breaks
Morning	06:00 - 14:00	120 minutes
Afternoon	14:00 - 17:00	60 minutes
Evening	17:00 - 01:00	120 minutes
Night	01:00 - 06:00	30 minutes

Table 14. Frequency of breaks for avoiding fatigue according to period of day

5. ***F5 Cumulative Fatigue***. To keep *cumulative fatigue* scores low, avoiding *late, night and early shifts* in a row is necessary, in combination with the required days off for a full recovery. For example, if a worker has two night shifts in a row his fatigue score will be 9, meaning that for a full recovery two days off in a sequence are needed. (Please refer to Figure 15) **Loop R7** will be weaker when fewer days in a row with late, night or early shifts are undergone and **loop B3** is made stronger if more days off are included minimizing the value for this factor and allowing *productivity* to be higher.

5.2 How to optimize Task Design (non-time related factors)

The policies highlighted in this part were generated by information provided in the Group Model Building session held by experts and by the knowledge obtained from the literature review. The measures suggested are not necessary novel. However, their value resides on highlighting the secondary effects that implementing them could have in the system.

6. **Disengagement from work**. More breaks don't necessarily mean the worker will restore their cognitive capacities adequately. An expert session was held with TNO experts to validate the model and determine possible model extensions. During the session, experts referred to the way the work environment, social support and socialization could act as a moderator to decrease the possible effects of fatigue or to increase recovery during breaks. Bosch, van Rhijn, and de Looze (2010) studied an alternating breaks scheme for shift workers during periods with a higher workload than usual. This approach consisted of adding 2 extra operators to the production line and experimenting a task design were operators would not have a general break but rather operators would have them in pairs. The previous was done to avoid a costly reconfiguration of the production line by adding workstations. The study was successful and lead to a performance increment. Even though it was reported that this **task design** was rated by workers as "pleasant" leading to no increased *mental workload*, one of the conclusions from the study was that this configuration should only be used during peak demand periods and for not longer than 2 months, as it would lead to decreased socialization possibilities during breaks with possibilities of impairing performance. Finally, a discussion of Sonnentag (2011)'s work presented in (Ackerman, 2011) between mental workload and cognitive fatigue experts (Hockey, Ackerman, Faber, Kanfer, Van Dongen) emphasized the importance of psychological detachment (being able to put thoughts away from work during free time) both within free time during work and outside of work. Detachment at lunch time was emphasized, exercising at mid-day and how disengagement during the work weeks predicted positive affect. The conditions so that workers can disengage from work during break and lunch time should be provided, a good work environment, social support and socialization would counterbalance cognitive fatigue increments.
7. **Training.** A simple measure to increase productivity and decrease *cognitive fatigue* is to provide training (Baines, 2007). Training would make **Loop R9** stronger and diminish *cognitive workload* as employees are able to produce more items per unit of time and as a result diminish *cognitive fatigue*. providing training can also increase *employee's motivation* (Capacity Performance Shaping Factor related to individuals) and this would result in a longer *Effort Incurred* from the employees, thus increasing *productivity*.
8. **Task switching**. Task switching, as arousal theory suggests can act as a stimulant and help operators being alert and motivated (Smit et al., 2003). This would result in increasing sustained effort time (making **loop B12** stronger), reducing *cognitive fatigue* (making **loop R10** weaker), impacting positively *productivity* (Making **Loop B11** Stronger) and act as a moderator for *cognitive fatigue* (making **loop R6** weaker). Nevertheless, the effect of task switching in the **Learning Curve Sector** must also be considered, as the forgetting effect caused by changing tasks could be detrimental (Givi, Jaber, & Neumann, 2015b). Task switching is not yet included in the system as it is a single-task model but the structure of the **Learning Curve Sector** could be used to represent this task configuration.

Finally, it is important to highlight that Fatigue Risk Management is the responsibility of both managers and workers. Managers should provide an environment, motivation, training and tools for workers to avoid burnout but employees are also responsible for using the resources obtained to prevent Fatigue (Lerman, Eskin, Flower, George, Gerson, Hartenbaum et al., 2012).

5.3 Conclusion

This section was divided into two parts giving policy recommendations for Time-related elements (**Fatigue Index** – **Cognitive Fatigue Sector**) and for Non-Time related elements (Other sectors). The policy recommendations were obtained from the literature research, expert sessions and case study results. As mentioned before the objective of this work was to explain rather than to optimize the system. In the future, it is recommended to first adapt the model to a specific sector and update parameters and effects of variables before intending to create policies. Nevertheless, this work does provide valuable insight as it helps to understand the relationship between the sectors and variables and helps to foresee the impact after understanding the causalities and nonlinearities present. Finally, it was also highlighted that Fatigue Risk Management within a manufacturing system is not only responsibility of managers but also employees need to account for it but still managers need to provide the necessary conditions for this to happen.

9. Discussion

This work aims to explain how cognitive factors can affect performance in a manufacturing setting by using a System Dynamics model. It was assessed whether such model could be used for prediction purposes or would only be useful for explanation and learning. Cognitive workload, sustained attention, task difficulty, task relevance, knowledge and are the main factors used to symbolize the previous. Which is possible due to their effect on *cognitive fatigue* (**human behavior outcome**) and this in turn on *productivity* (performance).

The model comprises 4 sectors: (1) **cognitive fatigue sector**, (2) **learning curve sector**, (3) **effort sector** and (4) **manufacturing sector**. The **cognitive fatigue sector** is based on the **fatigue index** (Rogers et al., 2009) and revised against the original model documentation. The integration of the four sectors was tested in order to assess structure and behavior robustness. A case study provided by the Netherlands organization of applied research TNO was used as a reference mode for the integrated system.

For determining **task characteristics** and **task design** elements and its relationship to **human cognitive factors**, the definitions from an integrated model of human factors commissioned by The Health and Safety Executive (2007) were used. Based on the results from the literature research, a second search was conducted to determine which evidence-based human performance/safety and health models were relevant to characterize the effects of **task characteristics** and **task design** on **cognitive factors**. The **fatigue index** was the model selected from nine possibilities obtained due to the suitability of the model for System Dynamics modeling, the variables involved, its relationship with cognitive human factors and modeling time requirements. The **task characteristics** and **task design** elements included in the **cognitive fatigue sector** come from **the fatigue index.** Two extra sectors were with the purpose was to correct the performance trend showed by the model (the selection of these two extra sectors was made from input from a Group Model Session held with experts and from the elements presented in the theoretical framework). The manufacturing sector was constructed to show the effects of human cognitive factors on productivity. To depict this effect, human behavior outcomes were used (*cognitive fatigue* and *error rate*). Several theories of cognitive factors and performance were studied. The entire model is based on elements captured in the elven theories that were analyzed. Nevertheless, the conflicting information portrayed in them and lack of data posed difficulties to create a model representation. The structure of this sector and the effect of *cognitive fatigue* on *productivity* were based on the molecules for system dynamics produced by (Eberlein & Hines, 1996). **Human behavior outcomes** (*cognitive fatigue*, *error rate*) in the model are a result of the task design (time-on-task, work schedules), **task characteristics** (sustained attention requirements, mental workload, task importance, task difficulty), the effect of **task design** and **task characteristics** on **psychological capacities** (*attentional resources*) and **capacity PSFs** (*learning and effort incurred*). The effect of **human behavior outcomes** on *productivity* is represented in the **manufacturing sector**, *cognitive fatigue* reduces *productivity, error rate* increases *work to do, effort incurred* increases *productivity* and *learning* increases the *maximum productivity rate*.

Two different set of policies were described that would ensure that *productivity* is maximized, one takes time-related factors into account (factors described in the **fatigue index** such as start time, end time, rest period length, breaks, shifts in a row) and the second refers to non-time-related factors such as training, task switching, etc. The first set of policies contributes by showing in a prescriptive form the information contained in the documentation of the fatigue index. The purpose of the previous was to help managers understand which time-related measures can be taken to avoid high values of *cognitive fatigue*. The second set of policies refer to the model as a whole and contribute by highlighting the positive and negative effects that a decision can have on the system.

The model was not able to reproduce the behavior for the variable *cognitive fatigue,* which suggests that a **generic model** cannot be used to predict performance in **all settings.** The **task characteristics** involved differ from activity to activity. For example, a manufacturing task might contribute to human cognitive capabilities impairments because of its degree of monotony, while in other circumstances the complexity of the task would be the main source. Dealing with monotony would require stimulation of the operator while dealing with complexity requires motivating employees, training, adequate rest time. Thus resulting in different structure needs for modeling each of those situations. Identifying the Performance Shaping Factors of each manufacturing task would then be the first step.

The behavior tests performed suggested that the structure of the model is correct and a further model adaptation to the specific case study could produce the desired behavior. Nevertheless because of value discrepancies in the literature, primary sources would be recommended as an adequate strategy for obtaining the information. The first version of the model only included the **cognitive fatigue sector** and its effect on the **manufacturing sector** but the **inadequate trend** in the results generated by the model for the variable *Productivity* made necessary the addition of the **Learning Curve Sector** and the **Effort Sector**. After the addition of these sectors, the model results showed a significant improvement. These two extra sectors improved the results of the model by adding extra **task characteristics** (task relevance and task difficulty) and **capacity performance shaping factors related to individuals** that haven't been included before in the model. The **learning curve sector** addition allowed the inclusion of the workers' **experience** (represented by knowledge) and the **effort sector** contributed by including in the model their attitudes (motivation – effort). The addition of the extra sectors, also contributed to the improvement in the results given by the model simulation because the dynamic structure was altered. Two balancing loops were added to the model to correct the trend and lead *productivity* closer to the desired goal. This addition allowed *productivity* to increase over time and not only decrease as a consequence of *cognitive fatigue*. An impairment of performance will then only happen when the consequences of *cognitive fatigue* on *productivity* are higher than the effect produced by *knowledge* and *effort*.

The Vensim optimization was used for assessing the structure of the **Cognitive Fatigue sector**, this led to a success on replicating the behavior for *cognitive fatigue*. The previous results suggest that System Dynamics can serve as a methodology to represent the effect of cognitive factors on performance (*productivity*), nevertheless for prediction purposes empirical research might necessary to determine the precise values of the parameters.

The theories found in the literature research give possible explanations of how **task characteristics** and **task design** can affect human cognitive capabilities. The theories also explain why performance impairments arise as a consequence of the previous. Nevertheless, conflicting explanations were found. The theories that were found to be more useful were merged theories because they not only give a possible explanation but also show interrelations between factors. Especially those showing more flexibility on the attribution of causes of cognitive impairments by englobing the mechanisms leading to the same outcome. For example, as indicated by (Langner & Eickhoff, 2013), performance impairments can be due to resource depletion or loss of executive control. Research on which theories lead to the same outcome for the same causes but with different mechanisms attributed can be beneficial to reduce divergence, increase understanding and facilitate further work on this topic.

The current work adds to the research on cognitive human factors and their effect on productivity. First, it is concluded that a generic model based on a bio-mathematical model (Fatigue Index) for this topic cannot be used for prediction purposes. The importance of determining the performance shaping factors for each task is suggested. As well, the importance of including **Capacity Performance Shaping Factors** for the creation of such a model is suggested. Second, it provides a synthesis of the **Fatigue Index** and **Learning Curve Sector** by creating a System Dynamics version of those quantified mathematical models. Third, the model includes elements of **task characteristics** that affect cognitive factors, no System Dynamics models were found addressing elements of task complexity during the literature review. Fourth, the model shows how the limitation highlighted by CASA for bio-mathematical models could be covered using System Dynamics, only phenotype was not considered as a general model was required. Fifth, this model contributes to the operationalization of factors included in cognitive factors theories. Operationalization of **Effort Sector** including task characteristics related to cognitive factors (task relevance, task difficulty). The **Effort Sector** is the only sector not based on an already quantified model and is based on empirical work (Stewart et al., 2009; Stewart et al., 2006) concerning the conceptual analysis of fatigue influence on cardiovascular responses (Wright, Stewart, & Barnett, 2008). Sixth, policy recommendations are done for both time-related aspects and non-time related ones. Insights obtained from the model construction were translated into policies. By using the Causal Loop Diagram created, a better understanding of the system can be done which can help managers understand their origin and its effect on the whole system.

The current work has an important number of limitations: First, limited access to information for both the construction of the **cognitive fatigue sector** and lack of direct access to primary data for the case study posed serious problems for replicating the behavior and estimating values of some variables, several assumptions had to be made. The model cannot be used to predict productivity. Second, the fatigue index was originally designed to be used for the rail sector in the UK and even if it has been used in industrial settings, it is not its primary focus. Third, the model was designed to run for 24 hours, even though the structure of the model allows for runs of several shifts in a row, shifts ending the next day (e.g. shifts with start time the previous day 16:00 and ending the next day at 02:00 in the morning) are not supported. **Effort Sector** would require adjustments for runs of several shifts. Fourth, the model contains boundary limitations, individual factors such as phenotype (morning or evening type) are not included, neither are environmental factors. Fifth, a further revision of the interpretation of the fatigue score can be beneficial as the fatigue index documentation does not provide great detail. Finally, the combination of continuous modeling with discrete events proved to be a challenge, due to the lack of experience as a modeler apprentice the structure of the model could need revisions. The development of this work was performed taking into consideration ethical practices. No harm was done to any of the participants of this project. All the participants in GMB sessions were informed of the purposes of the study. The participants were not forced in any way to participate in the sessions and had the freedom to withdraw at any point. No confidential information is being disclosed. The research was done intending to maintain scientific integrity during all the stages involved. There was no vested interests in the findings that could create bias.

Applying a System Dynamics perspective was beneficial as it allowed the addition of sectors and depiction of the relationships between them. It was also beneficial because it provided transparency. The mechanisms leading to the calculation of the factors can be identified in the structure of the model. Both, the causal loop diagram and the model structure can be used as a boundary object, facilitating communication with managers in organizations and increasing understating. The model can also be useful to generate awareness of the causalities behind the system. The behavior over time can be observed in the results provided by the simulation of the model, which allows further understanding of the underpinnings of the system. Which is not possible with the Fatigue Index, as it only provides the final fatigue score at the end of the shit, but it does not show how it developed over time. Finally, simulation proved to be beneficial for the validation of the model, as it helped in confirming that the initial dynamic hypothesis was incorrect. It was also useful to verify the assumptions made, as it could be proved that the addition of the extra sectors could lead to the desired behavior. Nevertheless, this methodology also posed some modeling and simulation difficulties, as several time factors and discrete events intervene (start time, break start and length), increasing the model complexity. Because of the previous the model had to be simplified in order to create the flight simulator and it does not cover all start times. A combination of System Dynamics with other methodologies could be advised for future work in the theme.

Some recommendations could be done for future research: First, the methodology followed could be optimized, an already quantified model aiming to represent a generic setting was used for this work and was tested using data from an existing case study. Because of the lack of agreement on the definition of terms related to cognitive factors, lack of agreement of theoretical frameworks and lack of already quantified models, creating a model specific to a situation first could be beneficial, rather than trying to adapt a generic one into the specific situation. It is also worth mentioning that even if creating a System Dynamics model translating an empirically tested quantified model is not a usual strategy when dealing with the lack of data sources and a high number of soft variables this strategy was helpful. Second, further research needs to be done on the effect of workload on fatigue for several work backgrounds, to revise the value of the parameters for these effects provided by the **Fatigue Index** as the optimization of the model showed that these values could improve the adequacy of the results provided by the model to those of the case study. Third, further research on the effect of cognitive factors on human behavior outcomes is necessary. Especially for the following effects: **effect of effort on fatigue, effect of fatigue on productivity, effect of effort on productivity, effect of fatigue on error rate.** Fourth, further research on human capabilities recovery would also be beneficial. Especially for quantifying the variables **fatigue depletion, effort recovery and motivation**. Finally, as previously mentioned focusing on reducing the divergence of theories could also be beneficial.

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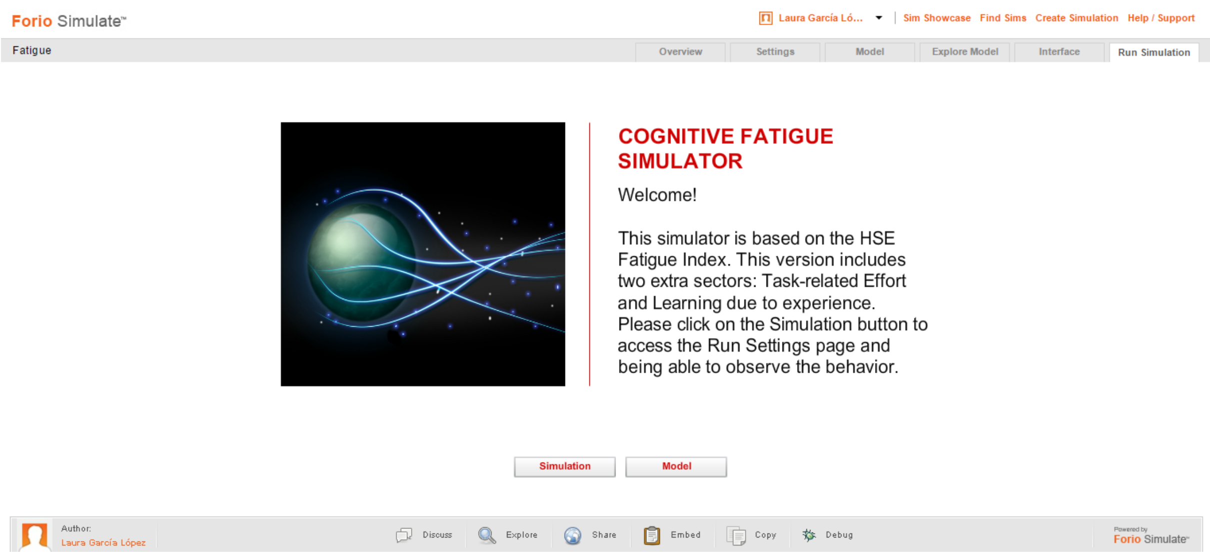
11. Annexes

Annex 1. Flight Simulator

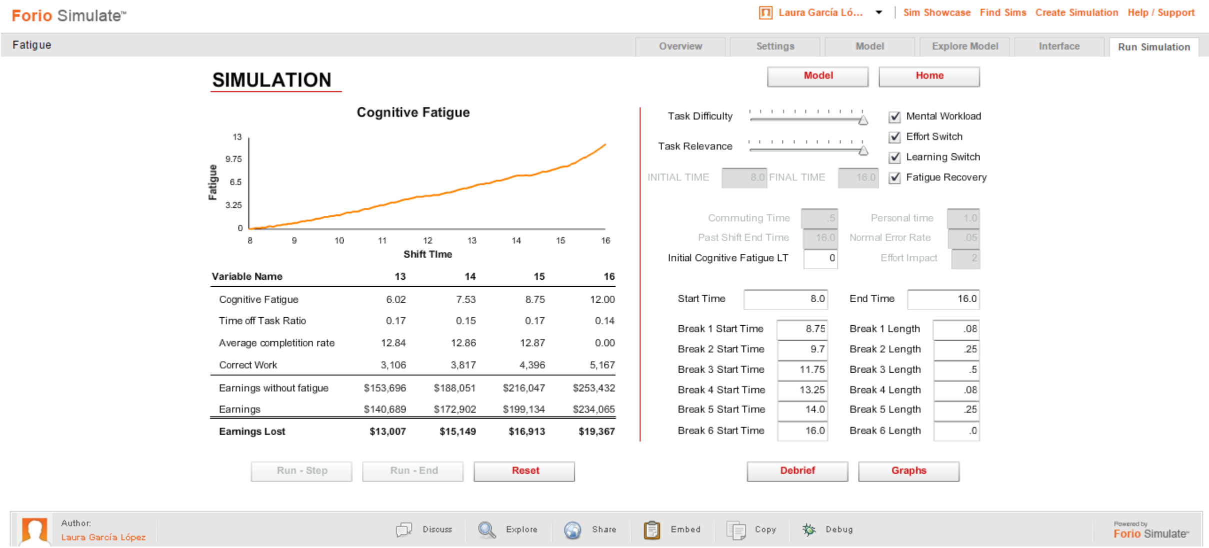
A simplified version of the model was used to create a Management Flight Simulator which can be accessed at the URL https://forio.com/simulate/laugarlop23/fatigue because of the complexity imposed by the high number of time structures included. The Flight Simulator Model Version only can be used for shifts starting between 8:00 hours and 14:00 hours, while the full model covers any time of the day.



The setup of the model includes the determination of Task Difficulty, Task Relevance, Whether Mental Workload exists for the task and the initial level of Cognitive Fatigue, Normal Error Rate and Effort Impact.

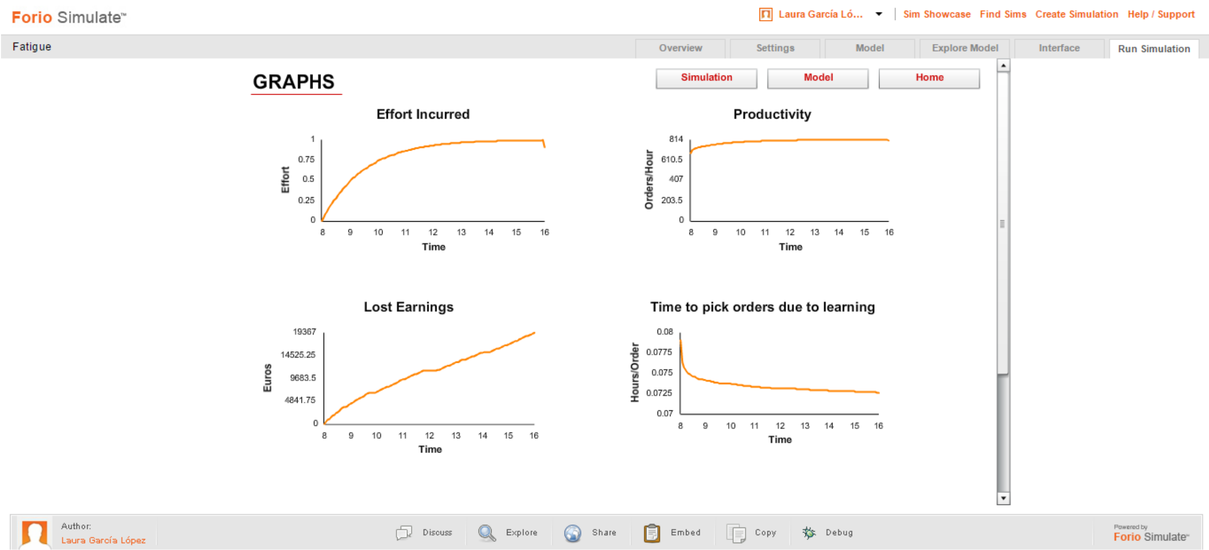
Time elements to specify: (1) Initial Time of the Model and End Time of the Model (period of time that is required to be covered). (2) Commuting time in hours and total hours required for Personal Time. (3) Past Shift End Time, (4) Start Time and End Time and (5) start time of breaks and length (if a break is not undertaken the length can be set to zero and it won't be considered).

The elements in the model that were included as extra can be de-activated so that the model gives the same results as the Fatigue Index. Mental Workload is treated as exogenous in the flight simulator, the **Effort Sector** and **Learning Curve Sector** can be de-activated and so does Fatigue Recovery. Factor 5 is also excluded from the model and should be calculated and specified as the value for Initial Fatigue.



Variable Name	13	14	15	16
Cognitive Fatigue	6.02	7.53	8.75	12.00
Time off Task Ratio	0.17	0.15	0.17	0.14
Average completion rate	12.84	12.86	12.87	0.00
Correct Work	3,106	3,817	4,396	5,167
Earnings without fatigue	$153,696	$188,051	$216,047	$253,432
Earnings	$140,689	$172,902	$199,134	$234,065
Earnings Lost	$13,007	$15,149	$16,913	$19,367

Finally, the graphs for the main variables involved in the behavior of the model are showed.



Annex 2. Time structures

Time within working cycle. This structure is used to represent time in a 24-hour format. Each time times reaches 24, the time within working cycle becomes zero. The computation of this structure was based on the work of Coyle (1985) for representing discrete events in a System Dynamics Model.

Face state. Indicates whether there is a shift going on, this variable takes a value on 1 whenever *Time Within Working Cycle* is higher than *Start Time* and lower than *End Time*. 1 = Shift on 0= Day off.

Switch Day on/off. This value can be specified directly in the model. A value of 1 represents a Day on duty and a value of 0 represents a day off for the worker.

Work Break Indicator. Whenever the worker is On Task, that is, whenever a break is not happening the *Work Break Indicator* will have a value of 1. The computation of this structure was based on the work of Coyle (1985) for representing discrete events in a System Dynamics Model.

On Task State. On Task State Reflects both, (a) If a shift is going on or not (b) if the workers are "On Task" or on a "Break" during that shift.

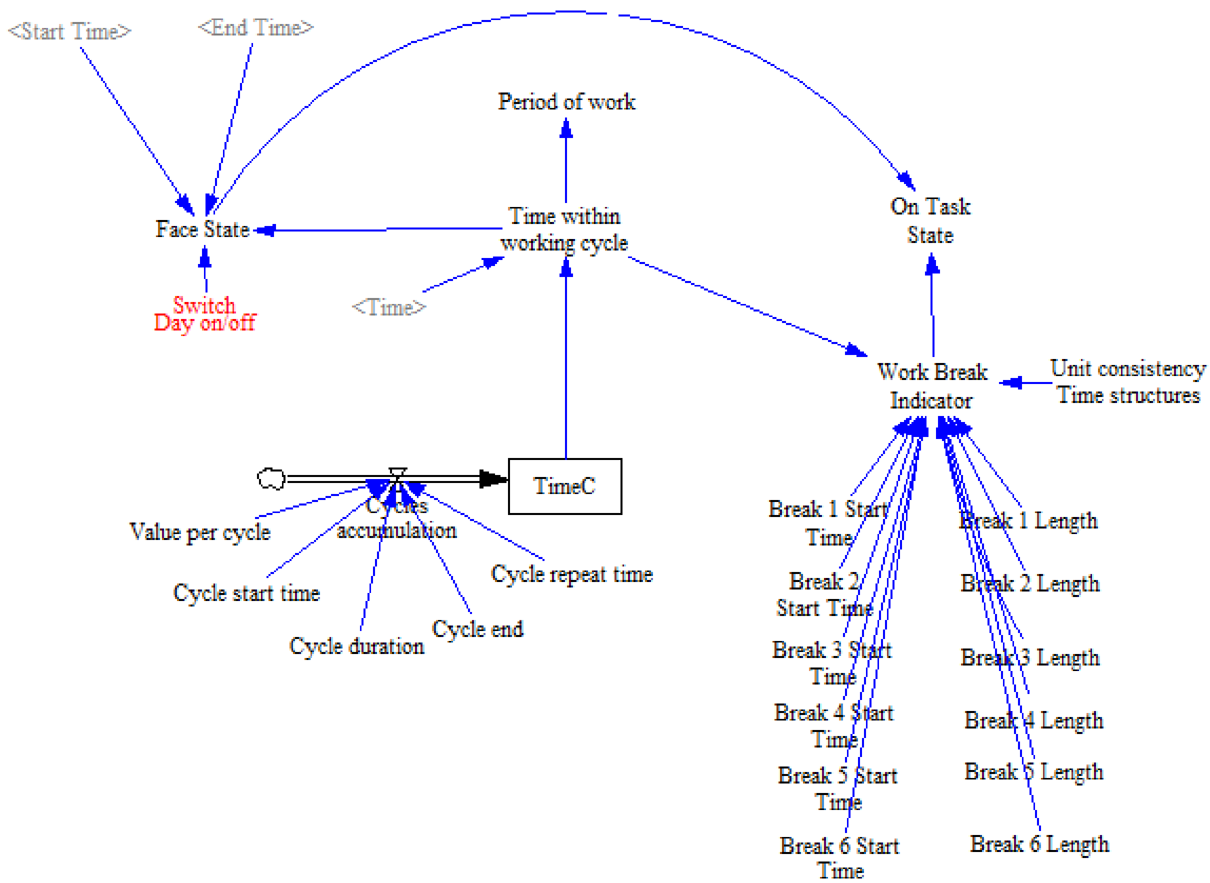


Figure 31. Time Structures

Finally, for Factor 5 Cumulative Fatigue to function, the structure shown in Figure 32 accumulates the number of Cumulative Nights, Early Shifts, Late Shifts and Days off.

Night. To determine whether or not a Night Shift is being undergone the same structure for the breaks is used and whenever the Face State is one (a shit is on) during 2.5 am and 4.5 am a value of 1 is assigned to the variable Night and this value is accumulated during the shift (24 hours). The cumulative nights after 1 shift would then be 1.

For Cumulative Early Shifts and Cumulative Late shifts the same procedure described for Cumulative Nights is used. Nevertheless, the determination of whether a shift is considered as Early or Late depends on the start time for Early Shift and the End Time for Late Shifts. In the case of days off the value of the switch is used to determine the existance of a day off. A day off would then trigger the depletion of these levels. Meaning that whenever the worker has a day off, the number of cumulative nights, early shifts, late shifts goes to 0. Days off depletion happens whenever the switch for Day on/off goes back to 1, that is whenever a new shift is started again.

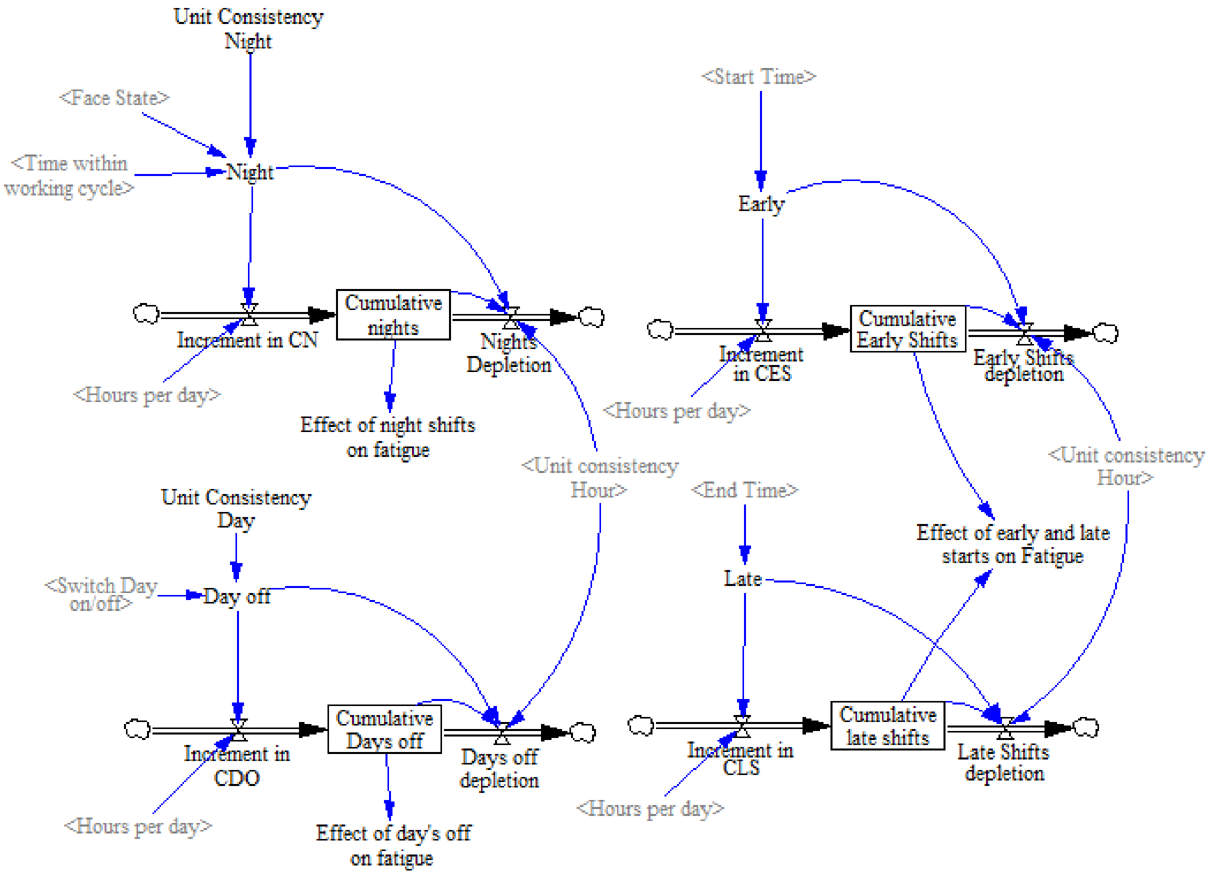


Figure 32. Cumulative shifts per time of the day of the shift

For each cumulative value (nights, days off, early shifts, late shifts) a non-linear function provides the fatigue increment for that period according to the information provided by Figure 32.

Effect of start time and shift length on fatigue

The effect of shift length for the calculation of *Factor 2 Shift duration* relies on both start time and shift length an IF THEN ELSE function is used for every possible start time (0 to 23) to obtain the Fatigue Value according to shift duration depending on the shift length. The Fatigue Value according to shift duration is the sum of all the "effects of start time on fatigue for shift duration" but only the one that is equal to the time the shift starts will be activated, all the other will have a value of zero.

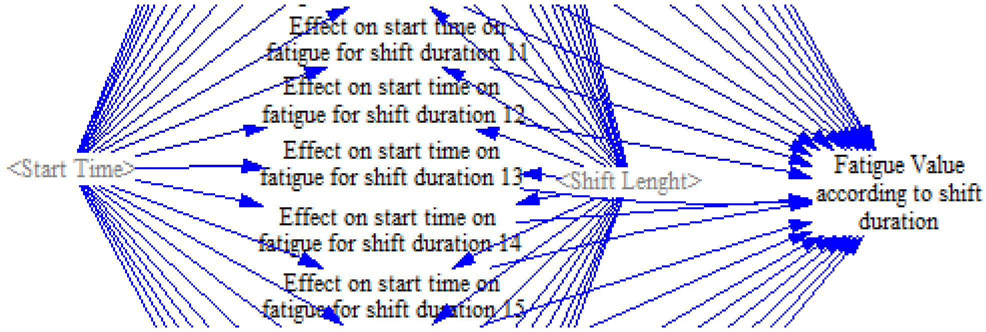


Figure 33.Effect of Start Time and Shift Length on Fatigue

Annex 3. Comparison of model values against the Fatigue Index

The original **fatigue index** provided an example of a calculated **fatigue index**, these values were used as an input for a validity check of the **Fatigue Index** section of the model. Note That some values might differ as the System Dynamics model takes into account exact times and the **fatigue index** rounds values up or down.

day	shift start	shift end	F1 score	F2 score	RSP score	RSP total	F3 score	sub-periods M/E	A	N	F4 score	shift type	score	CF score	F5 score	total score
1	7:00	15:00	7	0	0	0	0	7	1	0	0.5	D	0	0	0	7.5
2	4:40	15:00	11	4	0	0	0	8	1	1	1.5	E	3	3	3	19.5
3	15:00	2:00	4	6	0	0	0	8	2	1	2.0	L	3	6	6	18
4												O	-6	0		
5	21:30	5:30	13	0	0	0	0	4	0	4	4.0	N	5	5	5	22
6												O	-6	0		
7												O	-4	0		
8	10:00	21:15	1	2	0	0	0	8	3	0	1.5	D	0	0	0	4.5
9	15:00	23:00	4	0	0	0	0	6	2	0	1.0	D	0	0	0	5
10	9:00	20:45	2	2	5.2	73	4	9	3	0	1.5	D	0	0	0	9.5
11												O	-6	0		
12	17:00	5:00	7	10	0	0	0	8	0	4	4.0	N	5	5	5	26
13	17:00	5:00	7	10	3.5	49	2	8	0	4	4.0	N	4	9	9	32
14	17:00	5:00	7	10	3.5	49	2	8	0	4	4.0	N	3	12	12	35
15												O	-6	6		
16	11:00	15:00	1	0	0	0	0	3	1	0	0.5	D	0	6	6	7.5
17	5:00	17:00	11	8	0	0	0	8	3	1	2.5	E	3	9	9	30.5
18	4:00	17:00	12	11	4	60	3	8	3	2	3.5	N	5	14	14	43.5
19	11:00	23:00	1	3	0	0	0	9	3	0	1.5	D	0	14	14	19.5
20	15:00	5:00	4	13	0	0	0	8	2	4	5.0	N	5	15	15	37
total			92	79			11				37				98	317

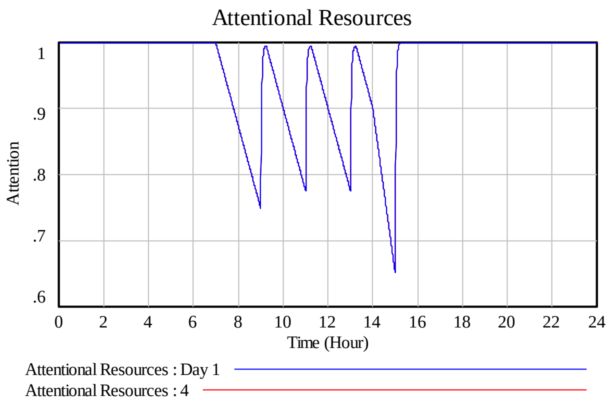
Figure 34. Example of calculated Fatigue Index

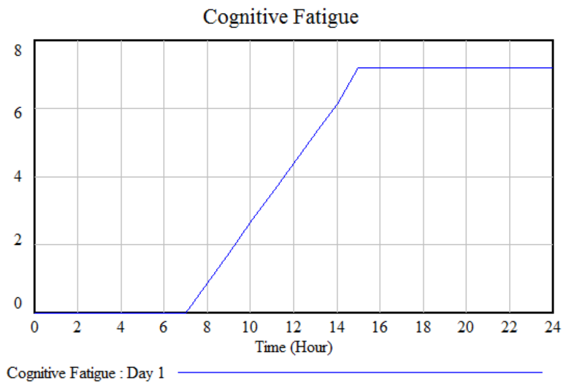
For each of the runs 15 minutes' breaks are taken after 2 consecutive hours of work, the workload is considered to be low and the activity requires sustained attention. A Test stock was created to identify the values for each shift for each factor.

Value discrepancies

Day 1

The value given by the model for day 1 is 7.20 while the value indicated by the **Fatigue index** is 7.5. The difference arises because the **Fatigue index** calculation involves counting the number of hours corresponding to the morning period as indicated in the description of Factor 4 and the number of hours corresponding to the afternoon period, then this number is multiplied by the corresponding score.





Time (Hour)	"Cognitive Fatigue" Runs: Day 1	Cognitive Fatigue
0		0
1		0
2		0
3		0
4		0
5		0
6		0
7		0
8		0.875
9		1.75
10		2.62881
11		3.50381
12		4.37881
13		5.25381
14		6.12881
15		7.19844

Figure 35. Cognitive fatigue Value at 15 hrs. for a shift starting at 7 and ending at 15 hrs. with low workload, sustained attention needed and a 15 minute break every 2 hours.

In this case, the shift length was 8 hours and it was composed of 7 morning hours and 1 afternoon hour. During the morning no periods of continuous work happened for more than 120 minutes meaning that the fatigue contribution score is 0. Nevertheless, after the last break, the working hours fall in two different periods, from 13:00 hrs. to 14:00 hrs. in the morning period, while from 14:00 to 15:00 hrs. in the afternoon period. In the afternoon, if 'time-on-task' with continuous sustained attention is higher than 60 minutes, a fatigue score of 0.5 per hour occurs. The calculation made by the **fatigue index** is to multiply 1 afternoon hour by the 0.5 fatigue per hour score, so the final score for Factor 4 is then 0.5. The System Dynamics model considers only actual worked hours and subtracts non-worked time (breaks) to determine the time-on-task, so starting from 13.15 attentional resources would be depleted, not starting from 13 as the **Fatigue Index** does.

First, from 13.15 to 14 hrs. the worker has been on the activity for only 45 minutes which for the morning period is not relevant, for the afternoon period it would be relevant only after 15 minutes more, meaning that only 45 minutes of the afternoon shift would contribute to fatigue giving a score of .375 final fatigue contribution from the breaks factor. Second, if the worker worked on a morning period during 45 hours and he can work with sustained attention during a longer time at this period and after 45 minutes of work in the afternoon, a lower fatigue result would be expected in comparison with a fully 2 hours work period in the afternoon.

The attentional resources stock accounts for this problems, using in the morning a lower depletion rate than in the afternoon and considering precisely the effect on the worker at different periods and durations of continuous sustained attention work. From 13:15 to 14:00 the morning depletion rate applies (.125) which means that the Attentional resources stock finishes at a level of .91 after the afternoon period and no contribution to Cognitive Fatigue has happened (when the attentional resources stock is below .75 the contribution starts). At 14 during the afternoon period the attentional depletion rate will change .25 attentional resources units per hour, making the stock arrive at a level of .75 in just an hour (in the morning period it takes 2 hours) and after 60 minutes of continuous work fatigue contributions from this factor will start. In day 1 the worker had already worked for 3/4 s of an hour but still at a morning rate and will only work for 60 minutes at the afternoon rate. As mentioned before when the morning period ends the worker has a level of .91 attentional resources, it is not 14:36 when a level lower than .75 is reached, meaning that the contribution of fatigue will only happen for 24 minutes (40% of an hour) meaning that the score for this factor should be 0.40* 0.5 fatigue units per hour = 0.20 fatigue units, which is in line with the result obtained .1984. This fact explains the need for considering Attentional Resources as mentioned in the Resources Theory and the contribution of adding this structure to the model.

Day 10

In comparison with the result given by the index 1.5, the System Dynamics version of the index gives a value of 5.5. The difference relies on the consideration of commuting time for both the end of rest period and the rest period lacking hours if these factors are ignored the **Fatigue Index** Vensim version provides the same number as the **Fatigue Index**.

*F3 = { [(Rest period score * Rest period Lacking hours) * (10 + number of exceeding hours)] / 20 } / Shift Length*

*F3 = { [(2.6 * 2) * (10 + 4)] /20 } = 73/20 = 4 fatigue units per day*

Shift start 09:00
Rest period 10 hours
Required Rest period 12 hours

Rest period Lacking hours = 12-10 = 2
Rest Period Score = 2.6
Shift Length= 12

Exceeding Shift hours = 12-8 = 4

If Commuting Time is considered, then the *Rest Period End* would not be given by the shift start but by the shift start – commuting time resulting in an RSP of 2 instead of 2.6 but a Required rest period of 13 hours.

Day 16

The shift schedule for day 16 is 4 hours long; the documentation of the index clearly states that the adequate proportion of the shift should be subtracted when it is shorter than 8 hours. The result given by the model is .5 vs 1 given by the index.

Final Results (Excluding Factor 5)

The calculation of factor 5 for shifts with an end time in the following day (e.g. Shift 3: start time 15:00 hrs. and end time 02:00 hrs. the next day). The model uses a 0 to 24 conversion of the elapsed time for accounting for *shift start and end* times for several days, when a shift ends the next day, the calculations of cumulative elements would comprise more than 24 hours, making the increments/decrements of Cumulative Fatigue (Factor 5) shorter/longer (as the accumulation of this value occurs during an entire day, 24 hours). In the case of shift 3 the day lasts 26 hours and shift 4 (Day off) would only last 22 hours. A change of all the time structures would need to be made to account for this factor.

#	Start Time	End Time	Length	Break Time (15 minutes)						FI						SD					
										F1	F2	F3	F4	F5	FI	F1	F2	F3	F4	F5	FI
1	7	15	8	9	11.3	13.25	-	-	-	7	0	0	0.5	0	7.5	7	0	0	0.2	0	7.2
2	4.66	15	10.34	6.66	8.91	11.16	13.41	-	-	11	4	0	1.5	3	19.5	11.3	4.67	0	1.43	3	20.43
3	15	2	11	17	19.3	21.5	23.75	26	-	4	6	0	2	6	18	4	6	0	1.09	6	17.09
4																					0
5	21.5	5.5	8	23.5	25.8	28	-	-	-	13	0	0	4	5	22	13.5	0	0	4.93		18.43
6	121																				
7																					
8	10	21.3	11.25	12	14.3	16.5	18.75	-	-	1	2	0	1.5	0	4.5	1	2.3	0	0.93		4.225
9	15	23	8	17	19.3	21.5	-	-	-	4	0	0	1	0	5	4	0	0	0.59		4.588
10	9	20.8	11.75	11	13.3	15.5	17.75	-	-	2	2	4	1.5	0	9.5	2	1.8	3.45	1.41		8.66
11																					
12	17	5	12	19	21.3	23.5	25.75	28	-	7	10	0	4	5	26	7	10	0	2.25		19.25
13	17	5	12	19	21.3	23.5	25.75	28	-	7	10	2	4	9	32	7	10	2	2.25		21.25
14	17	5	12	19	21.3	23.5	25.75	28	-	7	10	2	4	12	35	7	10	2	2.25		21.25
15																					
16	11	15	4	13	-	-	-	-	-	1	0	0	0.5	6	7.5	0.5	0	0	0.24		0.74
17	5	17	12	7	9.25	11.5	13.75	16	-	11	8	0	2.5	9	30.5	11	8	0	2.3		21.29
18	4	17	13	6	8.25	10.5	12.75	15	-	12	11	3	3.5	14	43.5	12	11	3.02	2.44		28.46
19	11	23	12	13	15.3	17.5	19.75	22	-	1	3	0	1.5	14	19.5	1	3	0	1.62		5.62
20	15	5	14	17	19.3	21.5	23.75	26	28.25	4	13	0	5	15	37	4	13	0	3.07		20.07

Table 15. Results comparison. Fatigue Index and System Dynamics Model

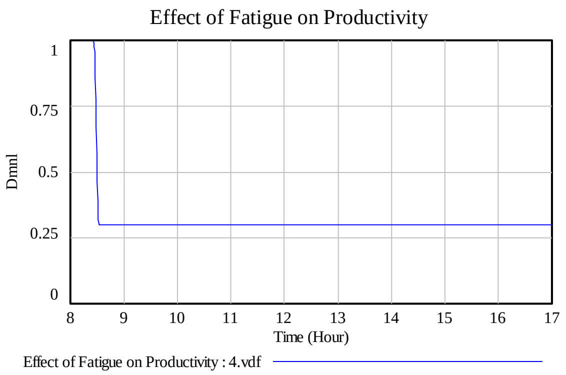
Annex 4. Validity Tests

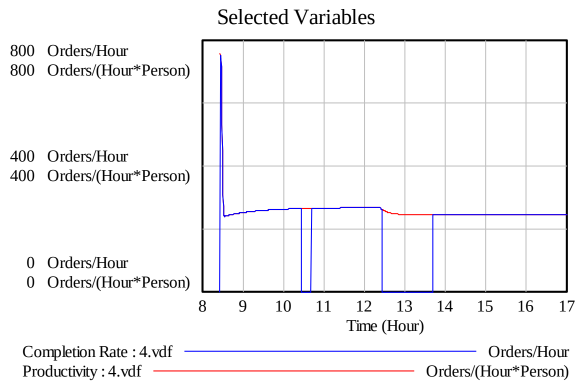
Extreme condition tests

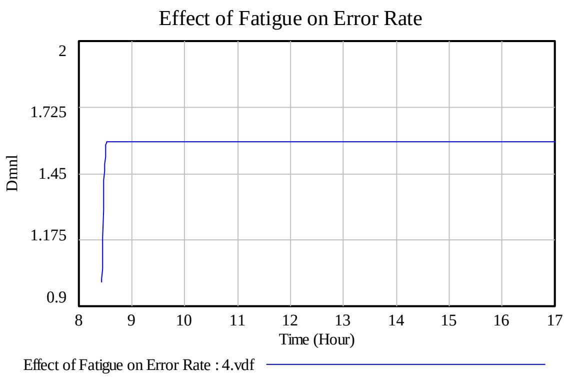
Cognitive Fatigue Sector

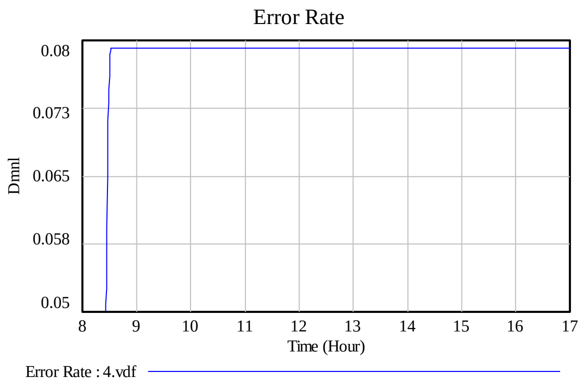
The state variable on which most rate equations rely is *cognitive fatigue*, this variable has an influence on *productivity*, higher levels of *cognitive fatigue* cause lower levels of *productivity* and this, in turn, defines the *completion rate*. *Cognitive fatigue* also affects the total amount of *correct work* that is completed by altering the *normal error rate*, higher levels of *cognitive fatigue* result in a higher *error rate* and as a consequence, the number of rework (*accomplishing incorrectly rate*) will be higher and a lower rate of *correct work* (*accomplishing correctly*).

To perform the test, the rate *fatigue increment* was set to 1000 fatigue units per hour. The maximum possible level the stock can have is 100 units and even with the higher rate of *fatigue increment* this limit was respected. The effect of fatigue on productivity had the adequate behavior, it must make productivity diminish a 70% when *cognitive fatigue* is equal to 100 (highest possible value) and the results indicated that this was done correctly. The *effect of Fatigue on error rate*, also presented the expected behavior, reaching the maximum possible value (1.58) and causing the error rate to increase from .05 to .08.









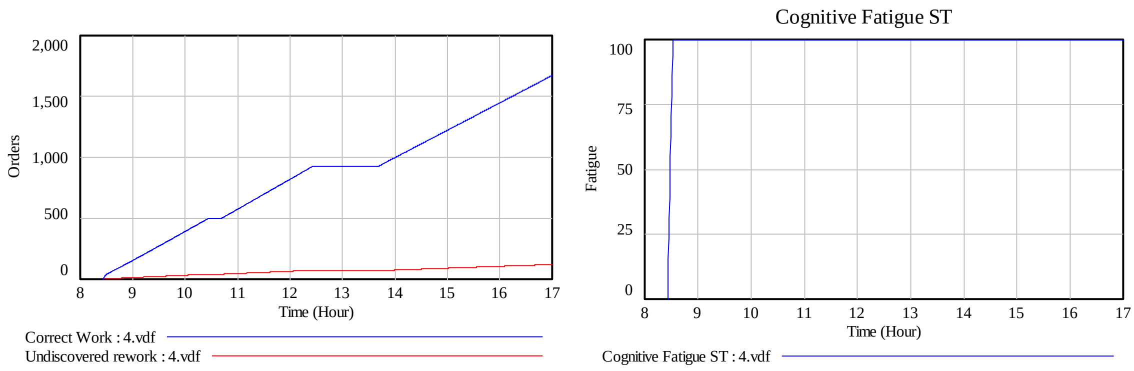


Figure 36 Simulation Results for Maximum Level of Cognitive Fatigue

When the inflow value for *Cognitive Fatigue ST* is changed to 1000 fatigue units/ hour with the objective of making the level reach it's higher value, there is no effect on the **Effort Sector**, as the value on which this sector relies on is only the initial *Cognitive Fatigue* Level. For being able to perform the test, the Initial *Cognitive Fatigue* Level was set to 100 fatigue/units (maximum possible value of this level) as the initial level of *Effort Incurred* is determined by the Initial level of *Cognitive Fatigue*. The expected behavior was that at time 8.43 the value for *Effort Incurred* would be 1 and it would approximate to zero as the high levels of fatigue produce no motivation on the employee to excise effort, and only when both effort resources and *motivation* are replenished (after a break), the worker would put some effort in its work.

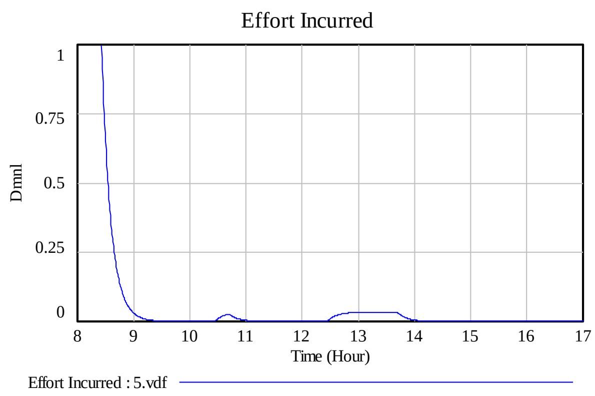


Figure 37. "Effort Incurred" as a consequence of Maximum possible value of Cognitive Fatigue Level.
Note: The parts where effort incurred is higher than zero after time 10 are due to Effort Recovery due to breaks.

The minimum possible value of the level *Cognitive Fatigue ST* is 0, the inflow for this level was set to 0 fatigue units per hour and the outflow was restored to its original formula. *Cognitive Fatigue ST* remains unchanged throughout the simulation. The expected effect on the **Effort Sector** is to have an initial *Effort Incurred* level equal to zero but a normal behavior; in the **Learning Curve Sector** there should be no direct effect; In the **Manufacturing Sector** the only expected consequence is for the minimum value to have an effect of value 1 for both *Effect of Cognitive Fatigue on Productivity* and *Effect of Cognitive Fatigue on Error Rate* , in other words, *Cognitive Fatigue* must not alter the values of the variables *productivity* and *error rate*. All the expected results were confirmed by the simulation.

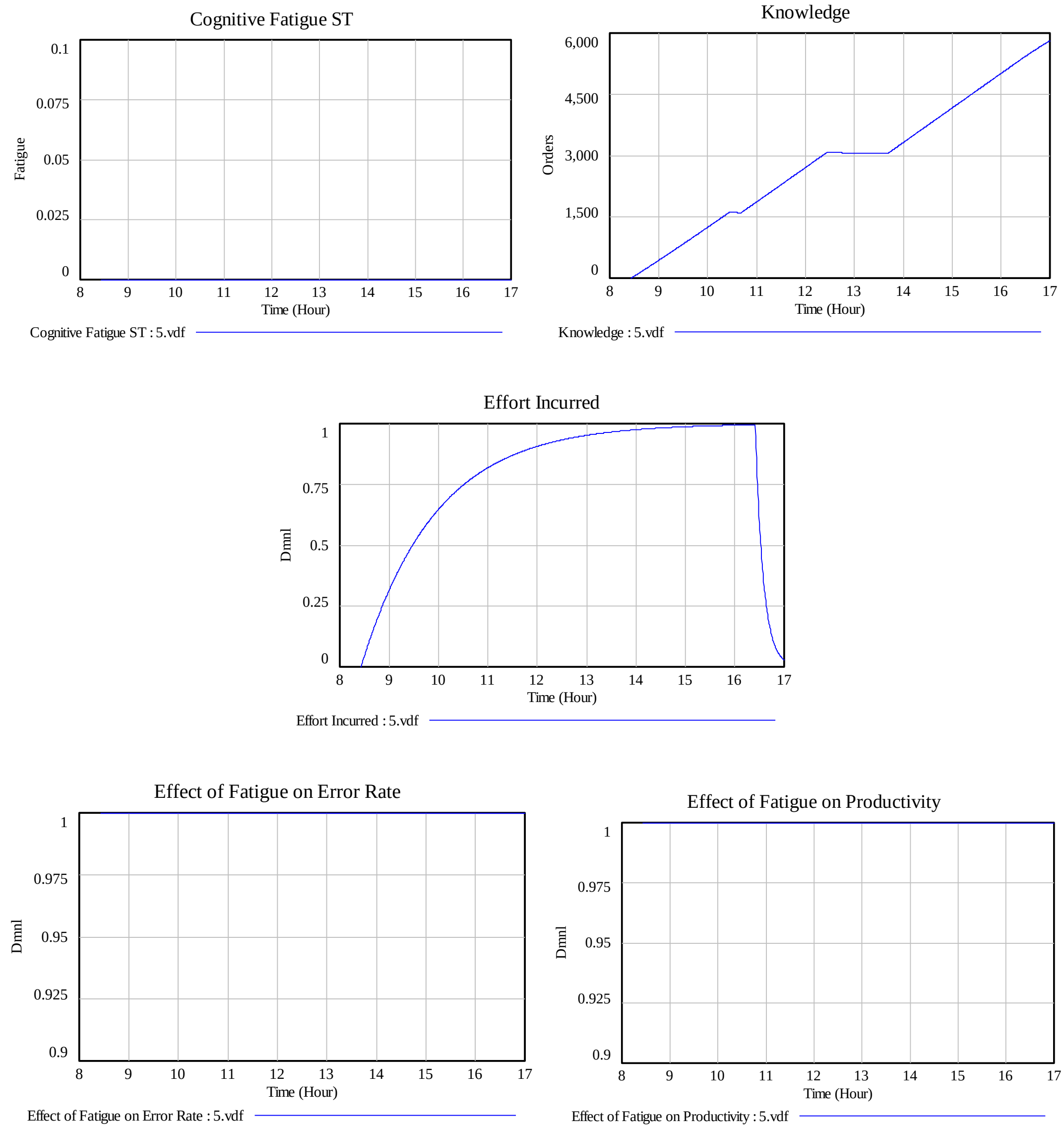


Figure 38. Simulation Results for minimum value of Cognitive Fatigue

The tests performed for the level *Cognitive Fatigue ST* were all passed successfully, indicating that it is consistent under extreme values.

Effort Sector

The levels contained in the **Effort Sector** have a minimum value of 0 and a maximum value of 1. The inflow and outflow were set to zero and the tests were doing setting the minimum and maximum possible figures as an initial value for the stocks. The only consequence on the system by the values is through the effect of *Effort Impact on Cognitive Fatigue* and the *Effect of Effort on productivity*. The values for these two effects were expected to reach the highest value set on the lookup function when the stock was set to 0 and the minimum one when the stock was set to 1. The test provided positive results. During this test the level *motivation* maintains its original value, as it is only influenced (depleted) by a change in the inflow to the level *Effort Incurred* and for the test, this rate had a zero value. A second test was performed to verify the correct behavior of *Motivation* when the inflow for *Effort Incurred* is above its limit, it was set to 1000 units per hour" and the *Motivation* level is depleted immediately, which was the expected behavior as the stock was set at its highest value

(1) and an outflow of 1000 units per hour for this stock means it goes immediately to zero, non-negativity was also confirmed.

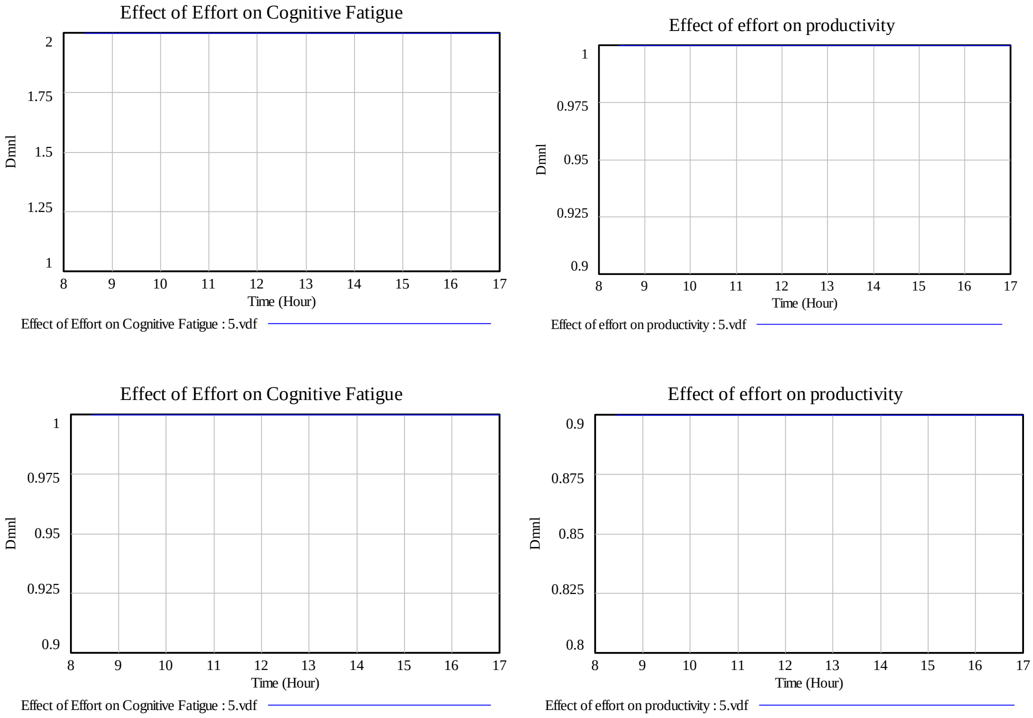


Figure 39. Effect of Minimum Level of Initial Effort Value on the System

Finally, the level *motivation* causes the depletion of the level *Effort Incurred*, this occurs when motivation reaches a number close to zero. This number is determined by the fraction of the original gap between (*maximum possible effort* and *initial effort*). For the test, the value of *Motivation* was set to zero and 1 (minimum and maximum possible values) and the behavior in the system was satisfactory.

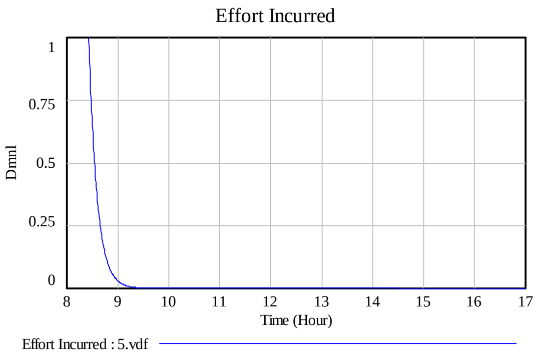


Figure 40. Effect of minimum value of motivation on Effort Incurred

Learning Curve Sector

As indicated beforehand, the level *Knowledge* accumulates every produced unit the worker(s) have created, based on this level, the *maximum productivity* will be calculated as a result of the learning effect achieved by the worker after performing the task. The first test performed consisted on setting the “Learning” Rate to 1,000,000 orders/hour, as the maximum level of this stock is infinity. The expected effects are: *Knowledge* to accumulate up to 8 million orders (the simulation is set to 8 hours), nevertheless this should just make *productivity* to increase but not alter considerably the normal behavior of the system because the learning function makes *productivity* to increase at a fast rate for the firsts orders, as the worker obtains new *knowledge* but as the worker becomes more experienced the possible learning per unit is minimal and it would get closer and closer to zero.

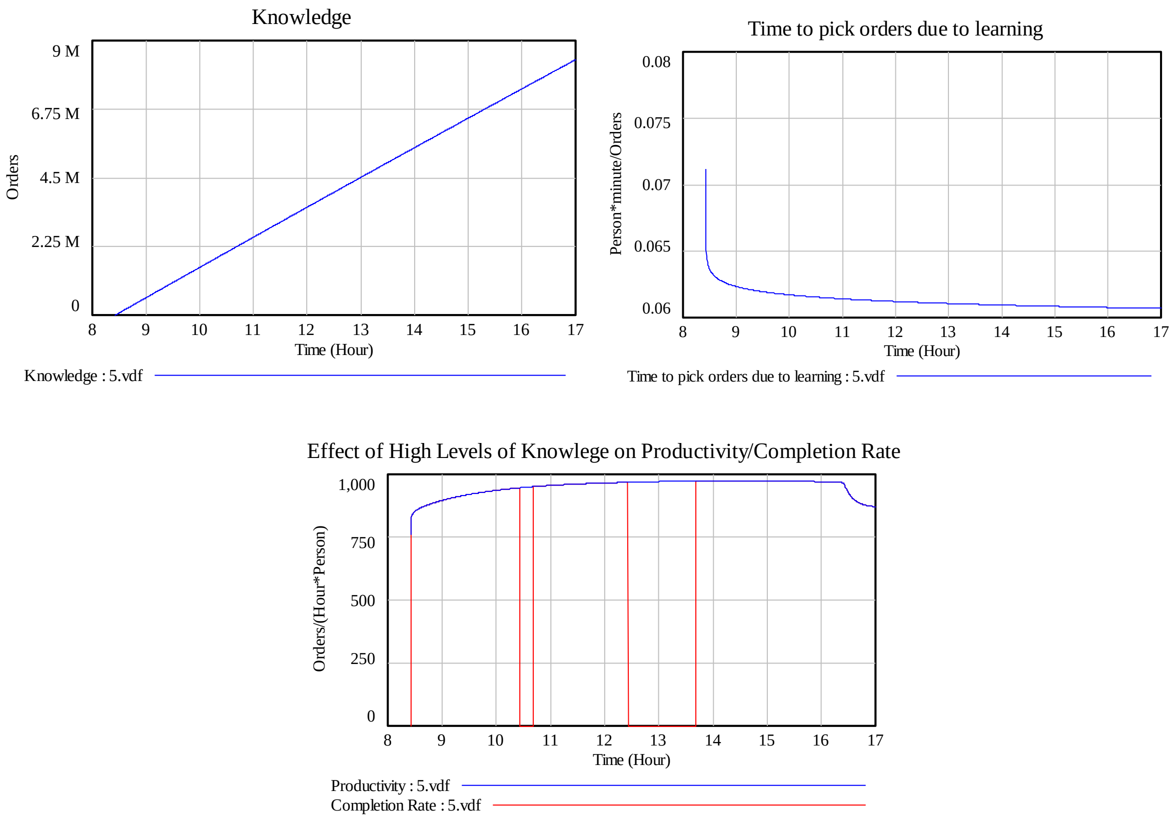


Figure 41. Effect of High Levels of Knowledge on Productivity/Completion Rate

With the objective of testing the effect of the minimum value of the level K*nowledge,* its initial value and inflow were set to zero. The expected effect on the system is *Maximum Productivity per hour* to not increase and to have the same value as *Normal Productivity*". The stock cannot go negative as it is protected with the outflow formulation (*Knowledge/Adjustment Time*). To test the system this level was given a negative value, but the result is the same as when the stock is set to zero, the value of normal productivity is maintained, as learning is only supposed to have an effect when *Knowledge* is higher than 0 and because the level protection, the negative value starts approaching zero automatically even without an inflow.

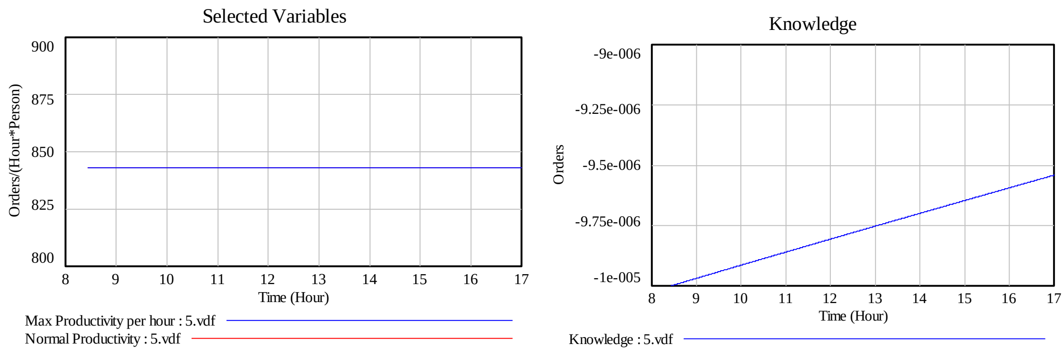


Figure 42. Effect of Minimum Values for Knowledge on the system.

Right: Knowledge level set to zero. Left: Knowledge level set to a negative number.

Manufacturing Sector

The manufacturing sector receives the effects of the previous 3 sectors and the behavior has already been proved when doing the tests for the previous sectors. Nevertheless, high values were assigned to stocks/flows to verify the behavior of this sector under extreme conditions. The inflow for *Work in Process inventory* was set to zero and the stock is set to zero, even if the workers have resources for production there is no change in *completion rate* as this situation would represent a scenario where there is no work to do for the operators. The minimum value for this stock is set to zero, a negative value was added for the outflow and the resulted behavior is also satisfactory and the same applies for the levels *Correct Work* and *Undiscovered Rework.*

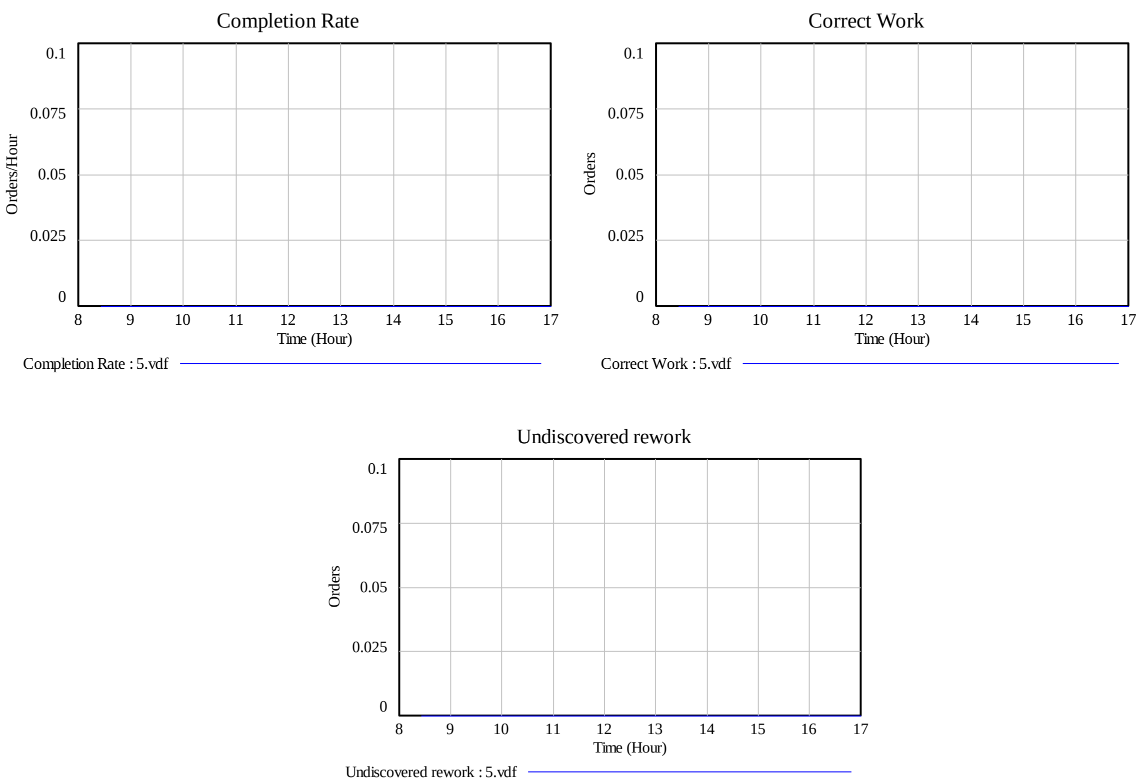


Figure 43. Effect of "Work in Process Inventory" on the manufacturing sector.

Behavior Anomaly Test

Loop Knockout Test 1. Effort Incurred.

Loops: R10. Effort Incurred and B11. Effect of Effort on Productivity were de-activated by changing the value of the variable *Time to Adjust Effort* from 8 (Normal Shift Length) to 365. **Loop R10** increases the *Fatigue Increment* resulting on a higher level of *Cognitive Fatigue* and this would result in a higher *Effort Incurred* on the next shift. **Loop B11** increases *Productivity per minute* as more *Effort Incurred* translates into a higher level of production, decreasing workload and decreasing Cognitive Fatigue. The effects were as expected, the value for both *Cognitive Fatigue* and *Productivity per minute* were lower in comparison to the base run as *Effort Incurred* had a minimal variation during the run due to the loop knockout, no anomalies were presented and the importance of the loop was justified.

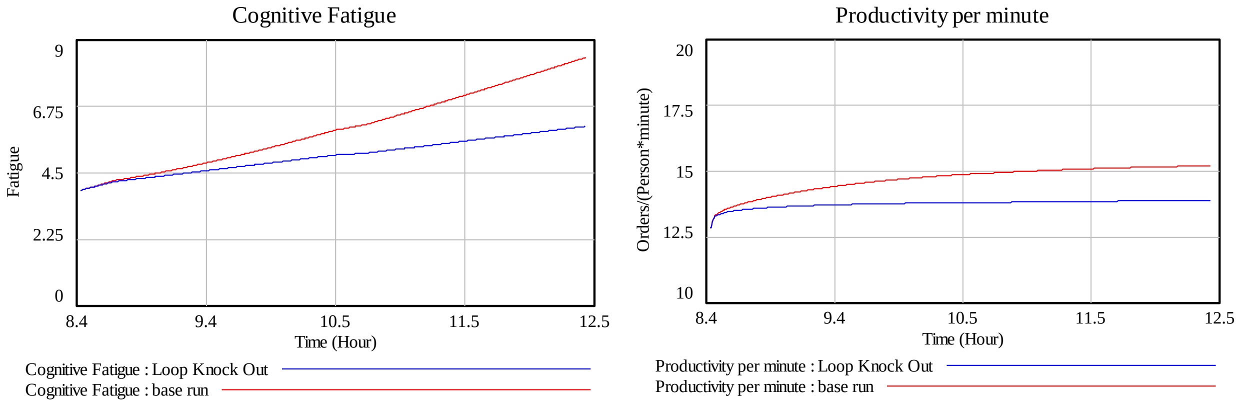
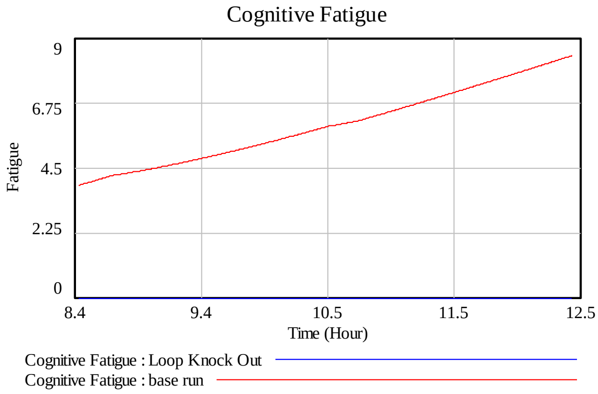
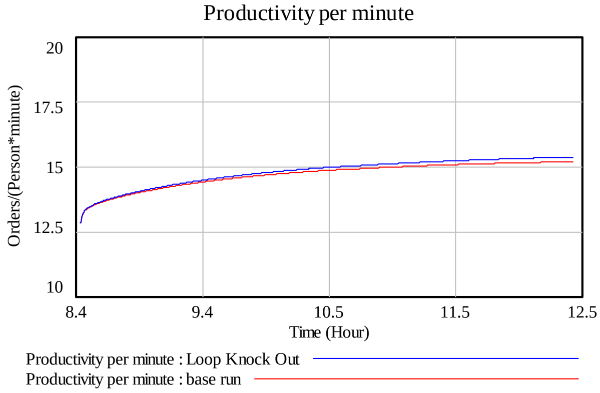


Figure 44. Loop Knockout . Effort Incurred.

Loop Knockout Test 2. Cognitive Fatigue

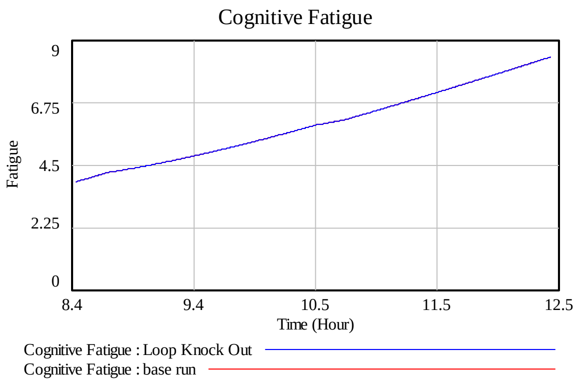
Loops B2. Break Time, R6. Effect of Time-on-task on CF and loop R10. Effort were knocked out by setting the initial value of *Cognitive Fatigue* and the *Fatigue Increment* rate during the entire simulation to zero. **Loop B2 and R6** act by increasing *Cognitive Fatigue* if activity in a task requiring sustained attention is continued without a break of 15 minutes for a determinate amount of time according to the period of the day (See Table 7) leading to a lower *productivity* (more *breaks* would diminish time-on-task and thus diminish *productivity*, while more time-on-task without breaks would increase *Cognitive Fatigue* and diminish *productivity* as well). ***Loop R6*** makes *Cognitive Fatigue* to Increase according to the shift start hour and the shift length, affecting productivity its value increases. Finally, ***Loop R10*** according to the initial *Cognitive Fatigue Level* increases the initial level of *Effort Incurred*, increasing productivity as well. No anomalies were found in the behavior showed by the analysis, nevertheless on Productivity, knocking out this loops cause a lower effect, meaning that they are less strong than those related to *Effort Incurred* (Loop Knockout Test 1).

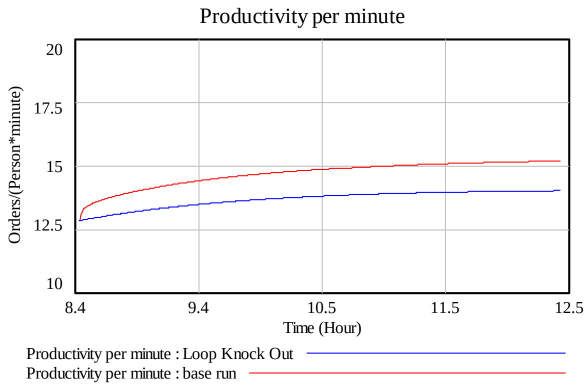




Loop Knock-out Test 3. Learning.

Loop R9. Learning was knocked out by setting the value of the variable *Effect of Knowledge on Time to Produce* to 1e-008, meaning that the effect of *Knowledge* won per each unit produced on the *Maximum Productivity* would be minimal. With a lower *productivity*, fewer orders will be completed per minute, creating even less *knowledge*. The results show that there is no effect on the values of *Cognitive Fatigue* but the value of *Productivity per minute* diminish considerably, proving no behavior anomalies and the importance of the loop.





Sensitivity Tests

Test 1

Assumption*: Cognitive fatigue* and *productivity* are sensitive to changes in *time to recover fatigue*
Decision: Time to Recover Fatigue varies between 0 to 4.5[6]

[6] (The Assumption used in the model Cognitive Fatigue Replenishment happens within 24 hours (24/5.3 = 4.3). 24 is divided by 5.3 (adjustment times) to ensure that the complete depletion of the stock happens after 24 hours, following the exponential decay behavior.

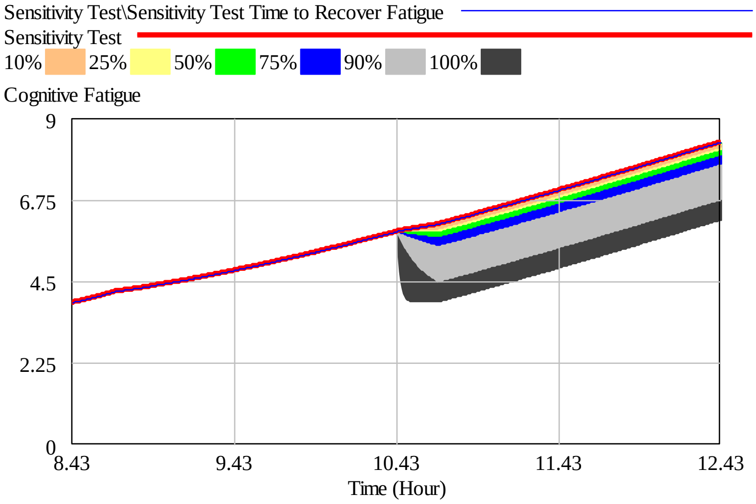


Figure 45. Sensitivity test. Effect of time to recover fatigue on cognitive fatigue

The results of Test 1 show that Productivity per minute is not highly sensitive to a change in the selected variable, as shown in Figure 46. Nevertheless, it should not be considered as a rule as high numbers of *cognitive fatigue* could lead to a different result. In contrast, the *variable cognitive fatigue* is, in fact, sensitive to the value of this parameter. The effect can be seen after 10.43 (a 15 minutes' break is set at this time in the model) because the variable "time to recover fatigue" only has an effect on cognitive fatigue when the worker is not "on task". As shown in Figure 45, the difference between the 10% Percentile and the 100% percentile is about -2.75 points. The sensitivity is numerical as it changes the numbers of the output of the simulation but not the behavioral pattern.

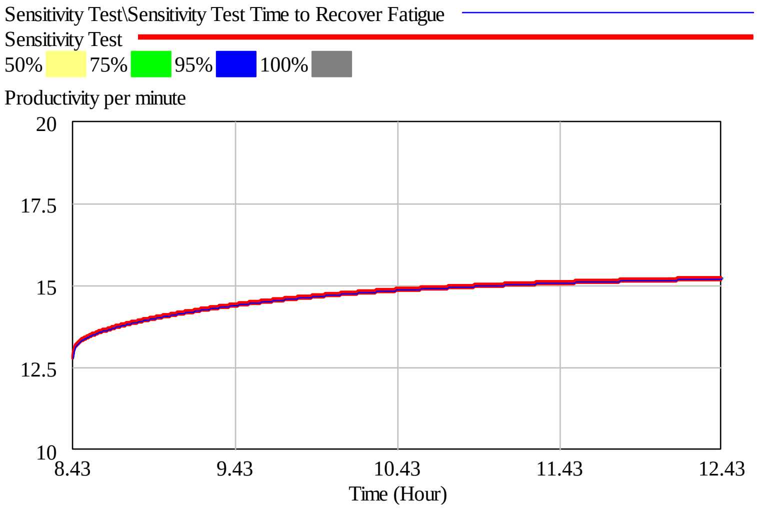


Figure 46. Sensitivity Test. Effect of Time to Recover Fatigue on Productivity per minute.

Test 2

Assumption: *Cognitive Fatigue* and *Productivity* are sensitive to changes in *Effort Impact*
Decision: *Effort impact* makes *Cognitive Fatigue increment* to vary from 0 to 5 times according to the *Effort Incurred* by the worker.

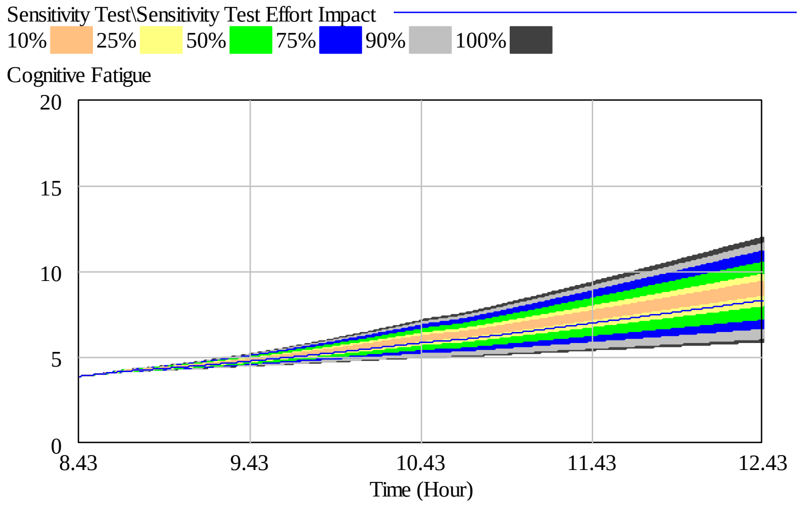


Figure 47. Sensitivity Test of Cognitive Fatigue to Effort Impact.

The results of Sensitivity Test 2 show that the variable *Cognitive Fatigue* is, in fact, sensitive to the value of Effort Impact. As shown in Figure 47, the difference of *Cognitive Fatigue* shown between the 10% Percentile and the 100% percentile is about +-2.5 points. The sensitivity is numerical there is a change in the numbers of the output of the simulation but not with the behavioral pattern.

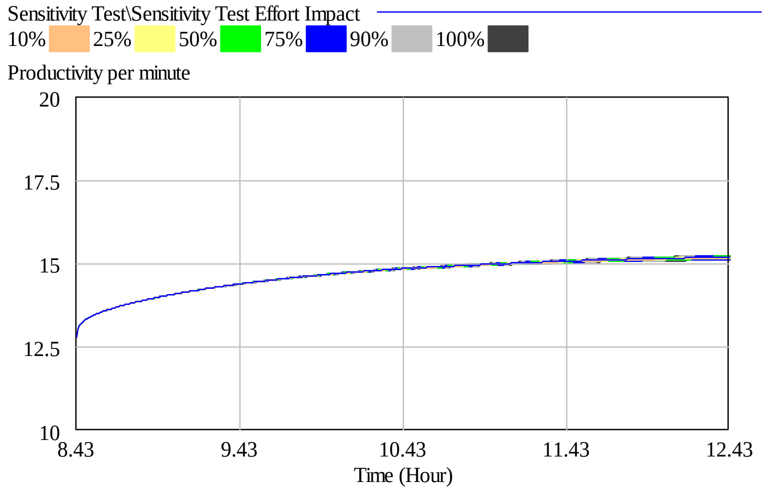


Figure 48. Sensitivity Test of Productivity per minute to Effort Impact

On the other hand, *Productivity per minute* is not highly sensitive to a change in the selected variable, as shown in Figure 48. Nevertheless, it should not be considered as a rule as high numbers of *Cognitive Fatigue* could lead to a different result.

Test 3

Assumption: *cognitive fatigue* and *productivity* are sensitive to changes in *task difficulty*

Decision: Task Difficulty varies between 0 to 1 which are the plausible values for this variable

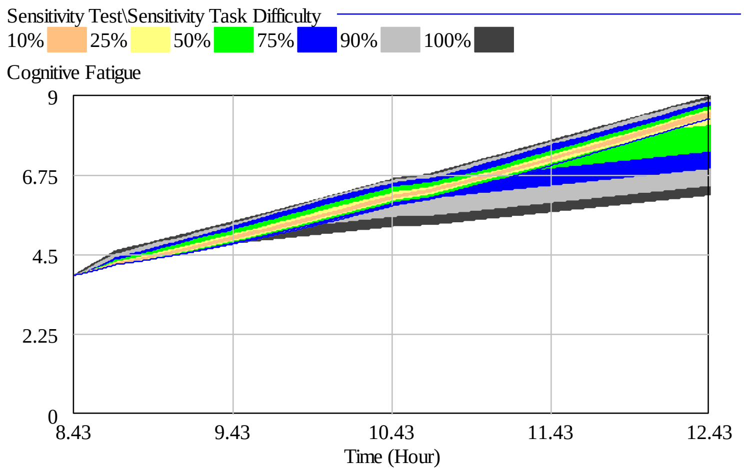


Figure 49. Sensitivity Test of Cognitive Fatigue to Task Difficulty

The results of Sensitivity Test 3 show that the variable *Cognitive Fatigue* is, in fact, sensitive to the value of Task Difficulty. As shown in Figure 49 Figure 47, the difference of *Cognitive Fatigue* shown between the 10% Percentile and the 100% percentile is of about -2.25 points. The sensitivity is numerical, as there would be a numerical change in the output of the simulation but no anomalies exist in the behavioral pattern. The higher *task difficulty* is, the higher *effort incurred* will be and the higher values *Cognitive Fatigue* will reach.

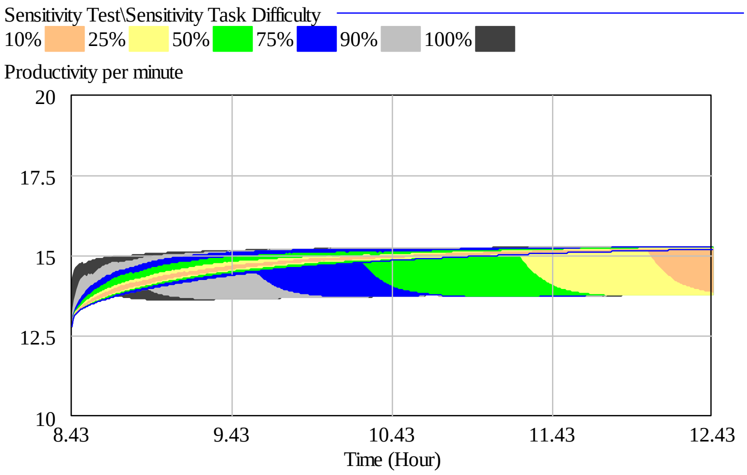


Figure 50. Sensitivity Test of Productivity per minute to Task Difficulty

In contrast to the results of the 2 previous sensitivity tests, in this case, *Productivity per minute* is sensitive to a change in the selected variable, as shown in Figure 18. The effect that *task difficulty* has on the value of this variable is due to the fact that *it* determines for how long *effort incurred* will continue to increase. When *Task difficulty* = 1, *Effort Incurred* will be sustained during the entire shift (8 hours), *Productivity per minute* will be higher as workers put a higher effort while performing the work. In contrast, when the value of *Task difficulty* is <1 the hours of continuous effort will be lower than 8, which justifies the decay observed in the behavior for percentiles higher than 10%. The sensitivity for this case is numerical, as the numbers of the output of the simulation change and no behavioral anomalies are shown.

Test 4

Assumption: *Cognitive fatigue* and *productivity* are sensitive to changes in *task importance*

Decision: *Task importance* varies between 0 to 1 which are the plausible values for this variable

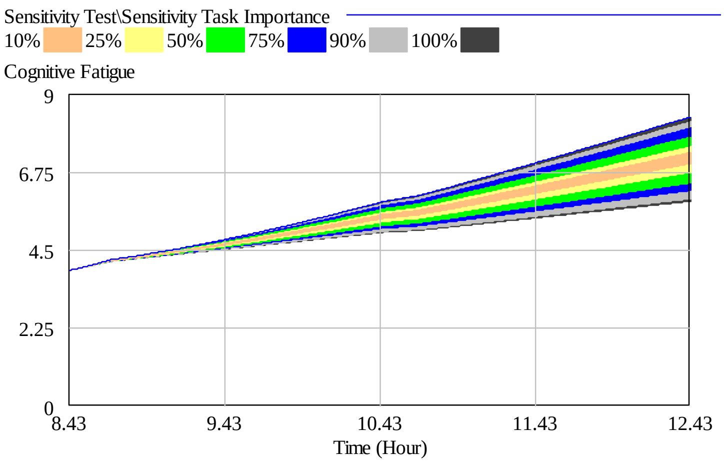


Figure 51. Sensitivity of Cognitive Fatigue to Task Importance

The results of Sensitivity Test 4 show that the variable *Cognitive Fatigue* is, in fact, sensitive to the value of Task Difficulty. As shown in Figure 49 Figure 47, the difference of *Cognitive Fatigue* shown between the 10% Percentile and the 100% percentile is about +-1 points. The sensitivity is numerical there is a change in the numbers of the output of the simulation but not with the behavioral pattern.

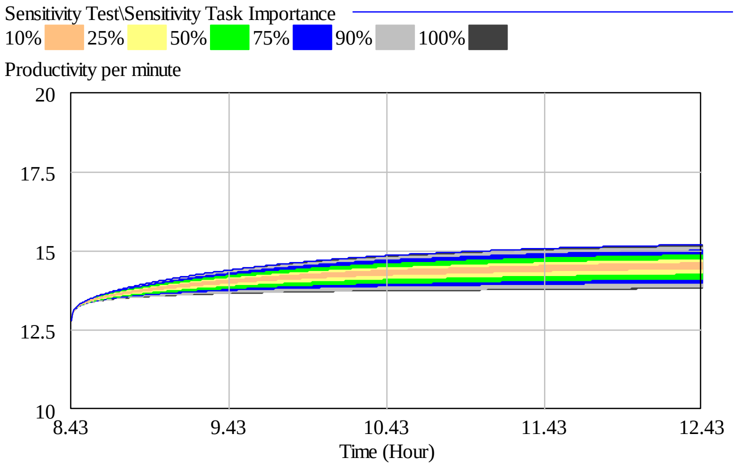


Figure 52. Sensitivity of Productivity per minute to Task Importance

Productivity per minute is sensitive to a change in the selected variable, as shown in Figure 18. *Task Importance* defines what will be the maximum number for *Effort Incurred*. The sensitivity is numerical; a change exists in the values of the output of the simulation but not on the behavioral pattern.

Annex 5. Model documentation

Accomplishing Correctly=

Completion Rate*(1-Error Rate)

Units: Orders/Hour

Accomplishing incorrectly=

Completion Rate*(Error Rate)

Units: Orders/Hour

Attention Use per hour per period=

0.125

Units: Attention/Hour/Period

Attention Use Rate=

Attention Use per hour per period*Effect of period of work on attention

Units: Attention/Hour

Attention Utilization Rate=

((Min (Attention Use Rate, Attentional Resources/TIME STEP))*Face State

-

Attentional Resources used/Average residence time*(IF THEN ELSE(On Task State =1, 0, 1)))

Units: Attention/Hour

Attentional Resources= INTEG (

-Attention Utilization Rate,

1)

Units: Attention [0,1]

Attentional Resources used= INTEG (

Attention Utilization Rate,

0)

Units: Attention

Average completion rate=

Accomplishing Correctly/Workers

Units: Orders/(Person*Hour)

Average residence time= 0.25/5

Units: Hour

Break 1 Length= 0.25
Units: Hour
Break 1 Start Time= 10.43
Units: Hour
Break 2 Length= 1
Units: Hour
Break 2 Start Time= 12.43
Units: Hour
Break 3 Length= 0.25
Units: Hour
Break 3 Start Time= 13.43
Units: Hour
Break 4 Length= 0
Units: Hour
Break 4 Start Time= 16
Units: Hour
Break 5 Length= 0
Units: Hour
Break 5 Start Time= 15
Units: Hour
Break 6 Length= 0
Units: Hour
Break 6 Start Time= 28.25
Units: Hour
BSMI=
Cognitive Fatigue*1.5
Units: Fatigue
Case Study = WITH LOOKUP (
Time,
([(0,0)-(18,60)],(8.43,5.88),(8.68,13.38),(8.93,21.38),(9.18,20),(9.43,23.25
),(10.18,25.63),(10.43,26.13),(10.68,19.25),(10.93,21.25),(11.18,24),(11.68
,25.25),(11.93,25.13),(12.18,25.75),(12.43,25.63),(17.6,25.63)))
Units: Dmnl
Change in F5=
IF THEN ELSE
(F5 Cumulative Fatigue<=0, MAX
(
((Effect of day's off on fatigue+Effect of early and late starts on Fatigue
+Effect of night shifts on fatigue)/Hours per day),0), ((Effect of day's off on fatigue
+Effect of early and late starts on Fatigue+Effect of night shifts on fatigue
)/Hours per day)
)
Units: Fatigue/Hour
Cognitive Fatigue= (Cognitive Fatigue ST+F5 Cumulative Fatigue)
Units: Fatigue

Cognitive Fatigue ST= INTEG (
Fatigue Increment-Fatigue Recovery,
0)
Units: Fatigue
Commuting Time= 0.5
Units: Hour
Completion Rate=
Min(Productivity*Workers,Work in process inventory/TIME STEP)*On Task State
Units: Orders/Hour
Completion Rate without Fatigue=
Max Productivity per hour*On Task State*Workers
Units: Orders/Hour
Consumption=
(Min(Effort Adjustment,Motivation/TIME STEP)
-Min(Depleted Motivation/Time to Recover Motivation,(Depleted Motivation/TIME STEP
))*(1-Face State))
Units: Dmnl/Hour
Correct Work= INTEG (
Accomplishing Correctly,
0)
Units: Orders
Correct work without fatigue= INTEG (
Completition Rate without Fatigue,
0)
Units: Orders
Cummulative Days off= INTEG (
Increment in CDO-Days off depletion,
0)
Units: Day
Cummulative Early Shifts= INTEG (
Increment in CES-Early Shifts depletion,
0)
Units: Day
Cumulative late shifts= INTEG (
Increment in CLS-Late Shifts depletion,
0)
Units: Day
Cummulative nights= INTEG (
Increment in CN-Nights Depletion,
0)
Units: Night
Cycle duration=
0
Units: Hour
Cycle end=

8000
Units: Hour
Cycle repeat time=
24
Units: Hour
Cycle start time=
24
Units: Hour
Cycles accumulation=
Value per cycle*PULSE TRAIN(Cycle start time, Cycle duration, Cycle repeat time
, Cycle end)
Units: Hour/Hour
Day off=
(1-"Switch Day on/off")*Unit Consistency Day
Units: Day
Days off depletion=
IF THEN ELSE(Day off=0, Cumulative Days off*30/Unit consistency Hour, 0)
Units: Day/Hour
Delay Time=
IF THEN ELSE(End Time>24, End Time, 24)
Units: Hour
Depleted Motivation= INTEG (
Consumption,
1-Motivation)
Units: Dmnl
Desired Completition Rate=
13
Units: Orders/(Hour*Person)
Discovering Rework=
Undiscovered rework/Time to discover Rework
Units: Orders/Hour
Early=
IF THEN ELSE(Start Time>4.5, 1, 0)-IF THEN ELSE(Start Time>6.99, 1, 0)
Units: Day

Early Shifts depletion=
IF THEN ELSE(Early=0, Cumulative Early Shifts*24/Unit consistency Hour, 0
)
Units: Day/Hour

Earnings=
(Correct Work*Items per order)*Price per piece
Units: Euro

Earnings without fatigue=

Correct work without fatigue*Price per piece*Items per order
Units: Euro

Effect of Attentional Resources on Fatigue = WITH LOOKUP (
Attentional Resources,
([(0,0)-(2,10)],(0,1.5),(0.067,1.5),(0.25,1),(0.49,1),(0.749,0.5),(0.75,0
),(1,0),(2,0)))
Units: Fatigue/Hour

Effect of Cognitive Fatigue on Fatigue increment= WITH LOOKUP (
Cognitive Fatigue ST/Maximum Cognitive Fatigue,
([(0,0)-(10,10)],(0,1),(0.9,1),(1,0)))
Units: Dmnl

Effect of day's off on fatigue = WITH LOOKUP (
Cummulative Days off,
([(0,-6)-(20,10)],(0,0),(1e-005,-6),(1,-6),(2.00001,-4),(20,-4)))
Units: Fatigue

Effect of early and late starts on Fatigue = WITH LOOKUP (
Cummulative Early Shifts+Cummulative late shifts,
([(0,0)-(10,10)],(0,0),(0.0001,3),(1,3),(1.1,2),(3.01,2),(4,2),(4.01,1),(
5.01,1),(6,1),(6.01,0),(7,0),(9,0)))
Units: Fatigue

Effect of Effort on Cognitive Fatigue=
Effort Switch*(Effort Incurred*(Effort Impact))+1
Units: Dmnl

Effect of effort on productivity= WITH LOOKUP (
Effort Incurred*Effort Switch,
([(0,0)-(10,10)],(0,0.9),(0.1,0.91),(0.2,0.92),(0.3,0.93),(0.4,0.94),(0.5
,0.95),(0.6,0.96),(0.7,0.97),(0.8,0.98),(0.9,
0.99),(1,1)))
Units: Dmnl

Effect of Fatigue on Error Rate= WITH LOOKUP (
Cognitive Fatigue,
([(0,0)-(100,2)],(0,1),(12.8866,1.0285),(20.615,1.096),(24.4845,1.2193),(
33.5051,1.3245),(50,1.444),(73.453,1.5328),(87.629
,1.5745),(100,1.5833)))
Units: Dmnl

Effect of Fatigue on Productivity= WITH LOOKUP (
Cognitive Fatigue,

([(0,0)-(100,1)],(0,1),(10.567,0.985),(26.5464,0.9504),(39.1752,0.858388)
,(50,0.737369),(59.536,0.605),(71.649,0.4467),(81.959,0.3517),(100,0.3)))
Units: Dmnl

Effect of Knowledge on time to produce= 0.0152
Units: Dmnl

Effect of Mental Workload on F1= 0.5
Units: Fatigue/Hour

Effect of Mental Workload on F2= 1.3
Units: Dmnl

Effect of motivation on effort depletion=
IF THEN ELSE(Motivation<=Percentage of original gap remaining, 1, 0)
Units: Dmnl

Effect of night shifts on fatigue = WITH LOOKUP (
Cummulative nights,
([(0,0)-(10,10)],(0,0),(1e-005,5),(1,5),(1.0001,4),(2,4),(2.0001,3),(3,3)
,(3.00001,2),(4,2),(4.00001,1),(5,1),(5.00001,0),(6.1,0),(10,0)))
Units: Fatigue

Effect of period of work on attention = WITH LOOKUP (
Period of work,
([(0,0)-(10,10)],(1,1),(2,2),(3,1),(4,4)))
Units: Period

Effect of Start Time on Fatigue = WITH LOOKUP (
Start Time,
([(0,0)-(24,20)],(0,13),(1,13),(2,13),(3,12),(4,12),(5,11),(6,9),(7,7),(8
,4),(9,2),(10,1),(11,1),(12,1),(13,2),(14,3),(15,4),(16,5),(17,7),(18,10),(
19,11),(20,12),(21,13),(22,14),(23,14),(23.9,14)))
Units: Fatigue

Effect on start time on fatigue for shift duration 0 = WITH LOOKUP (
IF THEN ELSE(INTEGER(Start Time)=0, Shift Lenght, 8),
([(0,0)-(16,22)],(0,0),(8,0),(9,2),(10,5),(11,7),(12,10),(13,13),(14,16),
(15,19),(16,22)))
Units: Fatigue

Effect on start time on fatigue for shift duration 1 = WITH LOOKUP (
IF THEN ELSE(INTEGER(Start Time)=1, Shift Lenght, 8),
([(0,0)-(16,22)],(0,0),(8,0),(9,2),(10,5),(11,7),(12,10),(13,13),(14,15),
(15,18),(16,21)))

Units: Fatigue

Effect on start time on fatigue for shift duration 10 = WITH LOOKUP (
IF THEN ELSE(INTEGER(Start Time)=10, Shift Lenght, 8),
([(0,0)-(16,22)],(0,0),(8,0),(9,0),(10,1),(11,2),(12,3),(13,4),(14,5),(15
,7),(16,9)))
Units: Fatigue

Effect on start time on fatigue for shift duration 11 = WITH LOOKUP (
IF THEN ELSE(INTEGER(Start Time)=11, Shift Lenght, 8),
([(0,0)-(16,22)],(0,0),(8,0),(9,0),(10,1),(11,2),(12,3),(13,5),(14,7),(15
,9),(16,11)))
Units: Fatigue

Effect on start time on fatigue for shift duration 12 = WITH LOOKUP (
IF THEN ELSE(INTEGER(Start Time)=8, Shift Lenght, 8),
([(0,0)-(16,22)],(0,0),(8,0),(9,1),(10,2),(11,3),(12,4),(13,6),(14,8),(15
,11),(16,13)))
Units: Fatigue

Effect on start time on fatigue for shift duration 13 = WITH LOOKUP (
IF THEN ELSE(INTEGER(Start Time)=13, Shift Lenght, 8),
([(0,0)-(16,22)],(8,0),(9,1),(10,2),(11,4),(12,6),(13,8),(14,10),(15,13),
(16,15)))
Units: Fatigue

Effect on start time on fatigue for shift duration 14 = WITH LOOKUP (
IF THEN ELSE(INTEGER(Start Time)=14, Shift Lenght, 8),
([(0,0)-(16,22)],(8,0),(9,1),(10,3),(11,5),(12,7),(13,9),(14,12),(15,14),
(16,17)))
Units: Fatigue

Effect on start time on fatigue for shift duration 15 = WITH LOOKUP (
IF THEN ELSE(INTEGER(Start Time)=15, Shift Lenght, 8),
([(0,0)-(16,22)],(0,0),(8,0),(9,2),(10,3),(11,6),(12,8),(13,10),(14,13),(
15,16),(16,19)))
Units: Fatigue

Effect on start time on fatigue for shift duration 16 = WITH LOOKUP (
IF THEN ELSE(INTEGER(Start Time)=16, Shift Lenght, 8),
([(0,0)-(20,22)],(0,0),(8,0),(9,2),(10,4),(11,6),(12,9),(13,12),(14,15),(
15,17),(16,20),(20,20)))
Units: Fatigue

Effect on start time on fatigue for shift duration 17 = WITH LOOKUP (

IF THEN ELSE(INTEGER(Start Time)=17, Shift Lenght, 8),
([(0,0)-(16,22)],(0,0),(8,0),(9,2),(10,5),(11,7),(12,10),(13,13),(14,16),
(15,18),(16,21)))
Units: Fatigue

Effect on start time on fatigue for shift duration 18 = WITH LOOKUP (
IF THEN ELSE(INTEGER(Start Time)=18, Shift Lenght, 8),
([(0,0)-(16,22)],(8,0),(9,2),(10,5),(11,8),(12,10),(13,13),(14,16),(15,19
),(16,22)))
Units: Fatigue

Effect on start time on fatigue for shift duration 19 = WITH LOOKUP (
IF THEN ELSE(INTEGER(Start Time)=19, Shift Lenght, 8),
([(0,0)-(16,22)],(8,0),(9,2),(10,5),(11,8),(12,11),(13,14),(14,16),(15,19
),(16,22)))
Units: Fatigue

Effect on start time on fatigue for shift duration 2 = WITH LOOKUP (
IF THEN ELSE(INTEGER(Start Time)=2, Shift Lenght, 8),
([(0,0)-(16,22)],(0,0),(8,0),(9,2),(10,5),(11,7),(12,10),(13,12),(14,15),
(15,18),(16,21)))
Units: Fatigue

Effect on start time on fatigue for shift duration 20 = WITH LOOKUP (
IF THEN ELSE(INTEGER(Start Time)=20, Shift Lenght, 8),
([(0,0)-(16,30)],(0,0),(8,0),(9,3),(10,5),(11,8),(12,11),(13,14),(14,17),
(15,20),(16,23)))
Units: Fatigue

Effect on start time on fatigue for shift duration 21 = WITH LOOKUP (
IF THEN ELSE(INTEGER(Start Time)=21, Shift Lenght, 8),
([(0,0)-(16,22)],(0,0),(8,0),(9,3),(10,5),(11,8),(12,11),(13,14),(14,16),
(15,19),(16,22)))
Units: Fatigue

Effect on start time on fatigue for shift duration 22 = WITH LOOKUP (
IF THEN ELSE(INTEGER(Start Time)=22, Shift Lenght, 8),
([(0,0)-(16,22)],(0,0),(8,0),(9,2),(10,5),(11,8),(12,11),(13,13),(14,16),
(15,19),(16,22)))
Units: Fatigue

Effect on start time on fatigue for shift duration 23 = WITH LOOKUP (
IF THEN ELSE(INTEGER(Start Time)=23, Shift Lenght, 8),
([(0,0)-(16,22)],(0,0),(8,0),(9,2),(10,5),(11,8),(12,11),(13,13),(14,16),
(15,19),(16,22)))

Units: Fatigue

Effect on start time on fatigue for shift duration 3 = WITH LOOKUP (
IF THEN ELSE(INTEGER(Start Time)=3, Shift Lenght, 8),
([(0,0)-(16,22)],(0,0),(8,0),(9,2),(10,4),(11,7),(12,9),(13,12),(14,15),(
15,17),(16,20)))
Units: Fatigue

Effect on start time on fatigue for shift duration 4 = WITH LOOKUP (
IF THEN ELSE(INTEGER(Start Time)=4, Shift Lenght, 8),
([(0,0)-(16,22)],(0,0),(8,0),(9,2),(10,4),(11,6),(12,9),(13,11),(14,14),(
15,16),(16,19)))
Units: Fatigue

Effect on start time on fatigue for shift duration 5 = WITH LOOKUP (
IF THEN ELSE(INTEGER(Start Time)=5, Shift Lenght, 8),
([(0,0)-(16,22)],(0,0),(5,0),(8,0),(9,2),(10,4),(11,6),(12,8),(13,10),(14
,13),(15,15),(16,18)))
Units: Fatigue

Effect on start time on fatigue for shift duration 6 = WITH LOOKUP (
IF THEN ELSE(INTEGER(Start Time)=6, Shift Lenght, 8),
([(0,0)-(16,22)],(0,0),(8,0),(9,1),(10,3),(11,5),(12,7),(13,9),(14,11),(15
,13),(16,16)))
Units: Fatigue

Effect on start time on fatigue for shift duration 7 = WITH LOOKUP (
IF THEN ELSE(INTEGER(Start Time)=7, Shift Lenght, 8),
([(0,0)-(16,22)],(8,0),(9,1),(10,2),(11,3),(12,5),(13,7),(14,9),(15,11),(
16,13)))
Units: Fatigue

Effect on start time on fatigue for shift duration 8 = WITH LOOKUP (
IF THEN ELSE(INTEGER(Start Time)=8, Shift Lenght, 8),
([(0,0)-(16,22)],(0,0),(8,0),(9,0),(10,1),(11,2),(12,3),(13,4),(14,5),(15
,7),(16,9)))
Units: Fatigue

Effect on start time on fatigue for shift duration 9 = WITH LOOKUP (
IF THEN ELSE(INTEGER(Start Time)=9, Shift Lenght, 8),
([(0,0)-(20,22)],(0,0),(8,0),(9,0),(10,1),(11,1),(12,2),(13,3),(14,5),(15
,6),(16,8),(20,8)))
Units: Fatigue

Effort Adjustment=

Min(Net effort, Effort Resources/(TIME STEP))*Face State
Units: Dmnl/Hour

Effort Depleted= INTEG (
Effort Depletion-Effort Recovery,
0)
Units: Dmnl

Effort Depletion=
((Effort Incurred/Effort Depletion Time)*(Effect of motivation on effort depletion +(1-Face State)))
Units: Dmnl/Hour

Effort Depletion Time= 1/6
Units: Hour

Effort Impact= 2
Units: Dmnl

Effort Incurred= INTEG (
Effort Adjustment-Effort Depletion,
Initial Effort)
Units: Dmnl

Effort Recovery= (Effort Depleted/Time to Recover Effort)*(1-On Task State)
Units: Dmnl/Hour

Effort Resources= INTEG (
Effort Recovery-Effort Adjustment,
Maximum subjective Effort- Initial Effort
)
Units: Dmnl

Effort Switch= GAME (1)
Units: Dmnl

End of Rest Period=
Start Time-(Commuting Time)
Units: Hour

End Time= 17.52
Units: Hour

Error Rate= Normal Error Rate*(Effect of Fatigue on Error Rate)
Units: Dmnl

Exceeding Shift Time=
Shift Lenght-Normal Shift Lenght
Units: Hour

F1 Shift Start=
Mental Workload*Effect of Mental Workload on F1+IF THEN ELSE(Shift Lenght>
8,Effect of Start Time on Fatigue/Shift Lenght,Effect of Start Time on Fatigue
/Normal Shift Lenght)
Units: Fatigue/Hour

F2 Shift Duration=
IF THEN ELSE(Mental Workload=1 , (Fatigue Value according to shift duration
*Effect of Mental Workload on F2)/Shift Lenght, Fatigue Value according to shift duration
/Shift Lenght)
Units: Fatigue/Hour

F3 Rest Period=
((((Rest Period Score*Rest period lacking hours)*(10+ Exceeding Shift Time
)) /20)/Shift Lenght)
Units: Fatigue/Hour

F4 Breaks=
Effect of Attentional Resources on Fatigue
Units: Fatigue/Hour

F5 Cumulative Fatigue= INTEG (
Change in F5,
3.9167)
Units: Fatigue

Face State=
IF THEN ELSE(End Time<24, IF THEN ELSE(End Time-(24*INTEGER(End Time/24)
)>Time within working cycle, 1, 0)-IF THEN ELSE
(Start Time>Time within working cycle, 1, 0),
1+(IF THEN ELSE(Start Time>Time within working cycle, 0, 1)- IF THEN ELSE(
End Time-(24*INTEGER(End Time/24))>Time within working cycle
, 0, 1))
)*"Switch Day on/off"
Units: Dmnl

Fatigue Increment=
(((F2 Shift Duration+F1 Shift Start+F3 Rest Period+F4 Breaks)*Effect of Effort on Cognitive
Fatigue
)*(1-(1-Face State))

*Effect of Cognitive Fatigue on Fatigue increment)
Units: Fatigue/Hour

Fatigue Normalization=
100
Units: Fatigue

Fatigue Recovery=
(Cognitive Fatigue ST/Time to recover fatigue)*(1-On Task State)
Units: Fatigue/Hour

Fatigue Value according to shift duration=
Effect on start time on fatigue for shift duration 0+Effect on start time on fatigue for shift duration 1
+Effect on start time on fatigue for shift duration 2+Effect on start time on fatigue for shift duration 3
+Effect on start time on fatigue for shift duration 4+Effect on start time on fatigue for shift duration 5
+Effect on start time on fatigue for shift duration 6+Effect on start time on fatigue for shift duration 7
+Effect on start time on fatigue for shift duration 8+Effect on start time on fatigue for shift duration 9
+Effect on start time on fatigue for shift duration 10+Effect on start time on fatigue for shift duration 11
+Effect on start time on fatigue for shift duration 12+Effect on start time on fatigue for shift duration 13
+Effect on start time on fatigue for shift duration 14+Effect on start time on fatigue for shift duration 15
+Effect on start time on fatigue for shift duration 16+Effect on start time on fatigue for shift duration 17
+Effect on start time on fatigue for shift duration 18+Effect on start time on fatigue for shift duration 19
+Effect on start time on fatigue for shift duration 20+Effect on start time on fatigue for shift duration 21
+Effect on start time on fatigue for shift duration 22+Effect on start time on fatigue for shift duration 23
Units: Fatigue

FINAL TIME = 12.43
Units: Hour

Forgetting=
Knowledge/Time to forget
Units: Orders/Hour

History Cognitive Fatigue=
Cognitive Fatigue
Units: Fatigue

Hours needed for full rest = WITH LOOKUP (
End of Rest Period,
([(0,0)-(24,20)],(0,20),(3.9,20),(4,13),(8.9,13),(9,12),(12.9,12),(13,13)
,(18.9,13),(19,15),(19.9,15),(20,17),(20.9,17),(21,19),(21.9,19),(22,20),(23
,20),(23.9,20)))
Units: Hour

Hours per day=24
Units: Hours

Increment in CDO=Day off*1/Hours per day
Units: Day/Hour

Increment in CES=Early*1/Hours per day
Units: Day/Hour

Increment in CLS=
Late*1/Hours per day
Units: Day/Hour

Increment in CN= Night*1/Hours per day
Units: Night/Hour

Initial Past Shift End Time= 15
Units: Hour

Initial Effort= INITIAL(Normalized Fatigue Level)
Units: Dmnl

INITIAL TIME = 8.43
Units: Hour

Items per order=1.51
Units: Product/Orders

Knowledge= INTEG (Learning-Forgetting, 0)
Units: Orders

Late=
IF THEN ELSE(End Time>24, IF THEN ELSE(End Time>0, 1, 0)-IF THEN ELSE(End Time
>26.5, 1, 0), IF THEN ELSE(End Time>0, 1, 0)-IF THEN ELSE(End Time>2.5, 1,
0))*0+
IF THEN ELSE(End Time-(24*(INTEGER(End Time/24)))>0, 1, 0)-IF THEN ELSE(End Time
-(24*(INTEGER(End Time/24)))>2.5, 1, 0)

Units: Day

Late Shifts depletion=
IF THEN ELSE(Late=0, Cumulative late shifts*24/Unit consistency Hour, 0)
Units: Day/Hour

Learning= Accomplishing Correctly
Units: Orders/Hour

Learning Switch= 1
Units: Dmnl

Lost Earnings= Earnings without fatigue-Earnings
Units: Euro

Max Productivity per hour=
(1/Time to pick orders due to learning)*Minutes per hour
Units: Orders/(Hour*Person)

Maximum Cognitive Fatigue= 85
Units: Fatigue

Maximum subjective Effort= Task Relevance
Units: Dmnl

Mental Workload= WITH LOOKUP (
Time+Workload*Unit consistency Hour*Workload Switch,
([(0,0)-(24,10)],(0,0),(8.42,0),(8.43,1),(8.68,1),(8.69,0),(12.42,0),(13.42
,0),(13.43,1),(13.68,1),(13.69,0),(17.52,0)
,(24,0)))
Units: Dmnl

Minute= 1
Units: minute/minute

Minutes per hour= 60
Units: minute/Hour

Motivation= INTEG (
-Consumption,
Maximum subjective Effort-Initial Effort)
Units: Dmnl

Net effort=
((Maximum subjective Effort-(Effort Incurred))/Time to adjust Effort)

Units: Dmnl/Hour

Night=
((IF THEN ELSE(Time within working cycle>2.5, 1, 0)-(IF THEN ELSE(Time within working cycle >4.3, 1, 0)))*(Face State))*Unit Consistency Night
Units: Night

Nights Depletion=
IF THEN ELSE(Night=0, Cumulative nights/Unit consistency Hour, 0)
Units: Night/Hour

Normal Error Rate=
0.05
Units: Dmnl

Normal Productivity= 14.3*60
Units: Orders/(Hour*Person)

Normal Shift Leght= 8
Units: Hour

Normalized Fatigue Level= Cognitive Fatigue/Fatigue Normalization
Units: Dmnl

On Task State= (Face State-Work Break Indicator)
Units: Dmnl

Original Gap= Maximum subjective Effort-Initial Effort
Units: Dmnl

Past Shift End Time= DELAY FIXED((End Time-(24*(INTEGER(End Time/24)))), Delay Time, Inital Past Shift End Time)
Units: Hour

Percentage of original gap remaining= EXP(-5.3)*Original Gap
Units: Dmnl

Period of work = WITH LOOKUP (Time within working cycle,
([(0,0)-(24,10)],(0,3),(0.99,3),(1,4),(5.99,4),(6,1),(13.99,1),(14,2),(16.9 ,2),(17,3),(24,3)))
Units: Hour

Personal time= 1
Units: Hour

Price per piece= 30
Units: Euro/Product

Productivity=
IF THEN ELSE(Learning Switch=1,
(Max Productivity per hour*Effect of Fatigue on Productivity)*(Effect of effort on productivity
)
, Normal Productivity*Effect of Fatigue on Productivity*(Effect of effort on productivity
))
Units: Orders/Person/Hour

Productivity per minute = A FUNCTION OF(Minutes per hour,Productivity)
Productivity per minute=
Productivity/Minutes per hour
Units: Orders/Person/minute

Rest Period=
(IF THEN ELSE(Start Time<=Past Shift End Time, 24-Past Shift End Time+Start Time
, Start Time-Past Shift End Time) -Commuting Time-Personal time)
Units: Hour

Rest period lacking hours=
MAX(Hours needed for full rest-Rest Period,0)
Units: Hour

Rest Period Score = WITH LOOKUP (
End of Rest Period,
([(0,0)-(30,10)],(0,1),(3.99,1),(4,2),(8.99,2),(9,2.6),(12.99,2.6),(13,3.5
),(18.99,3.5),(19,2.2),(19.99,2.2),(20,1.8),(20.99,1.8),(21,1.5),(21.99,1.5
),(22,1),(24,1)))
Units: Fatigue/Hour/Hour

SAVEPER =
TIME STEP
Units: Hour [0,?]

Shift Lenght=
IF THEN ELSE(End Time>24, 24-Start Time+(End Time-(24*INTEGER(End Time/24)
)), End Time-Start Time)
Units: Hour

Start Rate=
Work to do*On Task State
Units: Orders/Hour

Start Time=
8.43
Units: Hour

"Switch Day on/off"= GAME (
1)
Units: Dmnl

Task Difficulty= 1
Units: Dmnl

Task Relevance= 1
Units: Dmnl

TIME STEP = 0.0078125
Units: Hour [0,?]

Time to adjust Effort=
IF THEN ELSE(Task Difficulty=0, TIME STEP/5.3, (Task Difficulty*Normal Shift Lenght
)/5.3)
Units: Hour

Time to detect lag= 1
Units: Hour

Time to discover Rework= 24
Units: Hour

Time to forget= 365/2
Units: Hour

Time to pick first order=
(Minute/(Normal Productivity/Minutes per hour))
Units: Person*minute/Orders

Time to pick orders due to learning=
IF THEN ELSE(Knowledge<=0, Time to pick first order, Time to pick first order
*((Knowledge/Unit consistency Orders)^-Effect of Knowledge on time to produce
))
Units: Person*minute/Orders

Time to Recover Effort=24/5
Units: Hour

Time to recover fatigue=4.8

Units: Hour
Time to Recover Motivation=24/5.3
Units: Hour
Time within working cycle=
(Time-TimeC)
Units: Hour
TimeC= INTEG (Cycles accumulation, 0)
Units: Hour
Undiscovered rework= INTEG (Accomplishing incorrectly-Discovering Rework, 0)
Units: Orders
Unit Consistency Day=1
Units: Day
Unit consistency Hour=1
Units: Hour
Unit Consistency Night=1
Units: Night
Unit consistency Orders=1
Units: Orders
Unit consistency Time structures=1
Units: Dmnl
Value per cycle=3072
Units: Dmnl
Work Break Indicator=

```
        (IF THEN ELSE( Time within working cycle>Break 1 Start Time, 1, 0)-IF THEN ELSE
( Time within working cycle>Break 1 Start Time
         +Break 1 Length, 1, 0)+
        IF THEN ELSE( Time within working cycle>Break 2 Start Time-(24*INTEGER(Break 2 Start Time
/24)), 1, 0)-IF THEN ELSE( Time within working cycle
        >Break 2 Start Time-(24*INTEGER( Break 2 Start Time/24)) +Break 2 Length,
1, 0)+
        IF THEN ELSE( Time within working cycle>Break 3 Start Time-(24*INTEGER( Break 3 Start Time
/24)), 1, 0)-IF THEN ELSE( Time within working cycle
        >Break 3 Start Time-(24*INTEGER( Break 3 Start Time/24))+Break 3 Length, 1
, 0)+
        IF THEN ELSE( Time within working cycle>Break 4 Start Time, 1, 0)-IF THEN ELSE
( Time within working cycle>Break 4 Start Time
        +Break 4 Length, 1, 0)+
        IF THEN ELSE( Time within working cycle>Break 5 Start Time, 1, 0)-IF THEN ELSE
( Time within working cycle>Break 5 Start Time
        +Break 5 Length, 1, 0)+
        IF THEN ELSE( Time within working cycle>Break 6 Start Time, 1, 0)-IF THEN ELSE
( Time within working cycle>Break 6 Start Time
        +Break 6 Length, 1, 0))/Unit consistency Time structures
```

Units: Dmnl
Work in process inventory= INTEG (

Start Rate+Discovering Rework-Completion Rate,
0)
Units: Orders
Work to do=1620
Units: Orders/Hour
Workers= 1
Units: Person
Workload= WITH LOOKUP (
(Average completition rate/Time to detect lag)/Desired Completition Rate,
([(0,0)-(10,10)],(0,1),(0.5,0),(10,1)))
Units: Dmnl
Workload Switch=0
Units: Dmnl