A model for break scheduling assessment in manufacturing systems

1 Introduction

Human factors play an important role in any work and human unreliability can have serious consequences on system performance and safety at work. The identification and choice of a suitable risk assessment model has been considered a crucial issue for decades and many models were developed for different applications (Fera & Macchiaroli, 2010; Fera & Macchiaroli, 2009).These models rarely considered human factors, but there is little doubt that human errors contribute to the majority of incidents and accidents in high-risk systems, including nuclear power plants (NPPs), chemical and petrochemical industries, aviation, ships, road transportation, and railway systems (De Felice & Petrillo, 2011; Baysari, McIntosh, & Wilson, 2008), while they affect the quality and productivity in low-risk systems such as manufacturing or service (Di Pasquale, Iannone, Miranda, & Riemma, 2015a; Grosse, Glock, Jaber, & Neumann, 2015; Le, Qiang, & Liangfa, 2012). For this reason, over time, many researchers have focused on trying to understand and evaluate the concept of human error (Czaja, Nair, & Salvendy, 2012; Hollnagel, 1993; Reason, 1990) and considerable effort has been made to the development of Human Reliability Analysis (HRA) methods. The concern in reliability analysis is whether an operator is likely to make an incorrect action and which type of action is most probable (Hollnagel, 1996). For that purpose, HRA methods have been developed with the common objective of predicting the likelihood of occurrence for certain types of error and enabling safer and more productive designs. Several aspects of the work were considered to prevent and/or reduce the number of accidents and incidents and to improve the human performance. Many studies have focused on ergonomic interventions for improving musculoskeletal health and postural comfort (Battini, Delorme, Dolgui, Persona, & Sgarbossa, 2015; Naddeo, Cappetti, & D'Oria, 2015; Naddeo, Cappetti, Califano, & Vallone, 2014; Perez, de Looze, Bosch, & Neumann, 2014; Westgaard & Winkel, 1997), while others have focused on the impact of industrial shift systems with particular attention to long work hours and night shifts (Caruso, 2014; Folkard & Lombardi, 2006; Akerstedt, 2003; Smith, MacDonald, Folkard, & Tucker, 1998).

Rest breaks are a further aspect of considerable importance. Introducing breaks is a key intervention to provide recovery after fatiguing physical work to prevent growth of accident risks during working activities and improve human reliability (Di Pasquale et al., 2015a; Demerouti, Bakker, Sonnetag, & Fullgar, 2012; Jansen, Kant, & Van den Brandt, 2002; Dababneh, Swanson, & Shell, 2001). It is well known that work–break configurations influence the performance of individuals and can result in different productivity levels for individuals engaged in either mental or physical tasks (Bechtold & Thompson, 1993). Tucker, Folkard, and MacDonald (2003) analyze the impact of frequent breaks on different shift systems and confirms that the breaks, even for a short period, are reflected positively both physically and psychologically on the operator. Finding an optimal distribution across time of work breaks has been a challenge in ergonomics and operational research for almost an entire century, and it has also engaged management scientists (Rekik, Cordeau, & Soumis, 2010; Musliu, Schafhauser, & Widl, 2009; Aykin, 1996; Bechtold & Thompson, 1993).

A major problem in this field, from both a research and practical perspective, has been with respect to the appropriate technique for the development of effective work-rest policies that can be described by the number, timing, and duration of rest periods. To date the break scheduling problem has been addressed within the more general shift scheduling problem and numerous optimization algorithms and heuristic techniques have been proposed (Rekik et al., 2010; Musliu et al., 2009). Researchers in this field have traditionally concentred on the experimental approach to determine optimal work-rest schedules for specific tasks and under specified environmental conditions, considering human performance in terms of a generic work rate function. They have considered constrains as minimum break time, location of breaks, maximal working time without breaks in order to optimize the number of workers assigned to every shift and their work-rest policy (Aykin, 1996) or to maximize labour productivity, as measured by output per unit time (Bechtold, Janaro, & Sumners, 1984). The work rate performance is often modelled as a linear function without a detailed analysis of human reliability trend during the work shift and its qualitative effects on system performance (e.g. non-compliant items and reworking).

This paper presents the application of simulator for human error probability analysis (SHERPA) model for break scheduling assessment, through the match of the quantification of human reliability widely detailed in Di Pasquale, Miranda, Iannone, and Riemma (2015b) with the modeling of the operator's recovery because of one or more work breaks. SHERPA is able to predict the human error probability (HEP) and to assess the effects due to different human reliability levels through the evaluation of tasks performed correctly (Di Pasquale et al., 2015a, 2015b). In this paper, it is hypothesized that the breaks allow the mental and physical recovery and lead to improvements of human reliability. This, in turn, could lead to reduction of errors and increase of quality. The positive break impact on human reliability is a function of break time, location of break during the shift, recovery speed and type of performed activities. However, the break benefit is countered by increased idle time of employees during the rest period. The economic model proposed for SHERPA in this paper allows to evaluate the effects related to several different break configurations, considering the cost of lost production due to break and the quality costs related to operator errors.

The main research question is therefore the study of impact of different work-break policies in order to assess the qualitative and quantitative impacts of human reliability on the system performance and to identify the best work-break configuration. SHERPA, in fact, can simulate every possible scenario, changing the main important simulation parameters (e.g. type of performed activity, environmental factors, recovery rate, break length, number of breaks and economic features of process). The simulation results include human reliability trend during a whole work shift, effect of recovery on human performance due to rest period, quality reports (e.g. number of compliant and non-compliant items, number of performed reworks), economic results in terms of profits, revenues, quality costs, rework and break costs.

The paper is organized as follows. Section 2 highlights the relevance of human factors in system reliability and summarizes the state-of-the-art of Human Reliability Analysis approaches. Section 3 gives an overview of the work-break literature, considering the impact of breaks on human performance (well-being, recovery, and risk) and the break scheduling problems. The theoretical foundations and computational implementation of the SHERPA model are presented in section 4. Then the operating principles are discussed in a case study in section 5 where the simulation results are presented and analyzed. Finally, section 6 summarizes the main findings and discusses several research directions.

2 System reliability and human factors

Human factors cannot therefore be ignored when you define the reliability of a system. System reliability, in fact, refers to the dependability of performance of the system, subsystem, or system component in carrying out its intended function for a specified period (Czaja et al., 2012). The most widely accepted definition of reliability is the probability that a system will perform satisfactorily for at least a given period when used under stated conditions (Giuntini, 2000). Accordingly, the overall system reliability depends on the reliability of distinct components and their combination in the system. Most of the systems can be divided into three diverse functioning subsystems: the hardware/technical subsystem, software subsystem, and human subsystem (Figure 1).

The hardware/technical and software subsystems have, in general, a very high level of reliability, and the technical one is often designed to be partly or wholly fault tolerant, thanks to redundancies and protections (Hollnagel, 1998). During the past decades, the errors and accidents caused by failures of technical nature have considerably decreased due to advances in engineering and technology with an increase of system reliability, while human reliability has remained unchanged over the same period (De Felice & Petrillo, 2011). Human reliability is defined as the probability that each human component will perform successfully for an extended period, and its complementary is the HEP (Czaja et al., 2012).

Currently, despite the possibilities of automation, human labor is still needed in many industrial sectors and it has been estimated that 70%-90% of all accidents can be traced to human error (Di Pasquale et al., 2015b). The studies suggest, for instance, that up to 80% of all order picking warehouses are still operated manually on average because humans are able to extract heterogeneous items (in terms of weight, shape, volume) from their storage locations, which is difficult to imitate economically by machines and automated systems (Grosse, Glock, & Neumann, 2017; Grosse, Glock, Jaber, & Neumann, 2015). From a more theoretical viewpoint, human error has been shown to be a unique and important dimension of human performance in process plants. Two major approaches, probabilistic and causal, can be considered to characterize human error. The probabilistic approach is typically pursued by those interested in the human reliability aspects of risk analysis (Rouse & Rouse, 1983). In these analyses, human error is treated in a manner quite like that used for hardware failures. On the contrary, the causal approach assumes that errors are seldom random, and in fact, can be traced to causes and contributing factors which, once isolated, can perhaps be eliminated or at least ameliorated.

Due to the prevalence of human error and the huge and often costly consequences, its study has become an increasingly important research concern and an important focus within HRA, which has emerged as a well-defined discipline.

2.1 Human reliability analysis

HRA has evolved into a discipline that encompasses theoretical and analytic tools needed for understanding how human actions and decisions are influenced by the system's complexity and dynamics, the assessment of human errors that may arise during the work, and design interventions in the form of various barriers that can eliminate or mitigate these negative effects (Sharit, 2012). The purpose is to pursue quantitative estimates of human error probabilities during professional activity and their contribution to system risks (Baziuk, Rivera, & Nunez Mc Leod, 2012; Sharit, 2012). The 10-step HRA process proposed by Kirwan (1994) highlights the role of task and human error analyses in its earlier stages (Figure 2).

In the traditional HRA process, task analysis is used to describe and understand the human interactions with the system. The results of this phase allow error identification through appropriate error taxonomy. The analysts first define human failure events (HFEs), which are analyzed qualitatively and quantitatively, and then they assign relative HEPs to events. The qualitative analysis determines factors that enhance or degrade human performance and that might lead to the failure of the activity. These influencing factors include the features of the plant and the performance shaping factors (PSFs); these last are determined by the individual characteristics of the human being, environment, organization, or activity. Their goal is to provide measures to account for human performance.

There is no consensus to date on which PSFs should be used in HRA nor on the appropriate number of PSFs to include in an analysis. Some of the earliest HRA approaches adopted a single PSF, while a recent study commissioned by the US Nuclear Regulatory Commission (Good Practices for Implementing Human Reliability Analysis) identified the 14 essential PSFs for HRA (Kolaczkowski, Forester, Lois, & Cooper, 2005). This list of PSFs is not exhaustive but rather represents the minimum set of PSFs that should be considered in an HRA. There are numerous approaches to quantify HRA methods (Boring, 2015):

- Scenario matching methods: This approach, adopted by the technique for human error rate prediction (THERP) (Cacciabue, 1998; Kirwan, 1996), entails matching the HFE to the best fitting example scenario in a table and using the HEP associated with that template event as the basis for quantification.
- PSF adjustment methods: In methods, such as the standardized plant analysis risk-human reliability analysis method (SPAR-H) (Gertman, Blackman, Marble, Byers, & Smith, 2005) or cognitive reliability and error analysis method (Hollnagel, 1998), PSFs modify the nominal error rates. The effects of the PSF on the HEP in SPAR-H are summarized in the following equation as follows (Boring, 2010).

$$HEP_c = HEP_n \cdot PSF = \begin{cases} 0 < PSF < 1 \rightarrow \ HEP_c < HEP_n \\ PSF = 1 \quad\ \ \rightarrow \ HEP_c = HEP_n \\ PSF > 1 \quad\ \ \rightarrow \ HEP_c > HEP_n \end{cases} \tag{1}$$

  Here HEP_c and HEP_n are the contextual and nominal HEPs, respectively. Each PSF can have both positive and negative effects on performance, respectively decreasing or increasing the overall HEP.

- Expert estimation methods: These tools provide a structured means for experts to consider how likely it is for an error to occur in a scenario.
- Simulation based methods: Although currently uncommon, these methods use cognitive modeling and simulation to produce a data framework that may be used in quantifying the likelihood of human error (Di Pasquale, et al., 2015b; Boring, 2007, 2006; Mosleh & Chang, 2007).

Bell and Holroyd (2009) identified 72 human reliability related tools developed since the early 60s and classified them into three categories: first, second, and third generation. Each generation pursues the final HRA aim but develops the steps shown in Figure 2 with greater or lesser detail. The first-generation HRA methods focus on quantification in terms of success/failure of actions, with less attention paid to in-depth causes and reasons of observable human behavior (Di Pasquale, Iannone, Miranda, & Riemma, 2013; Cacciabue, 2004).

The second one is characterized by the consideration of cognitive and organizational factors, with an emphasis on qualitative aspects, interaction, and factors' interdependences.

The HRA methods proposed over the years have not always been particularly useful to the purpose for which they were developed. The review processes (Di Pasquale et al., 2013; De Felice, Petrillo, Carlomusto, & Romano, 2012) demonstrated that HRA criticism may be classified into three key issues: (1) model's theoretical basis (including taxonomy and concept's specificity), (2) definition and use of PSFs with heavy reliance on expert judgment in selecting PSFs, and use of these PSFs to obtain the HEP, and (3) HRA quantification. In particular, the quantification method is weak and the quantitative results are unsubstantiated since many methods pay attention only to the responses of humans in accident scenarios. Furthermore, HRA approaches have been mainly developed for high-risk contexts (e.g., aviation or NPPs) wherein only the typical accident scenarios are considered; therefore, much effort needs to be applied in different fields such as manual assembly or manufacturing systems (Sammarco, Fruggiero, Neumann, & Lambiase, 2014; Le et al., 2012; Schemeleva, Duriex, & Caux, 2012).

Currently, no methodology has a general consensus, and most of them have not been very attractive to the practitioners and managers due to the complexity of the techniques developed and the lack of information that allows implementation in a comprehensive manner (Rivera, Baziuk, & Núñez McLeod, 2011).

3 Rest breaks and work-rest policies

There are different methods that may be used to improve human performance and reduce errors, as previously underlined. The selection of adequate work-rest policies through the introduction of appropriate breaks is a very efficient approach even if it is not widely applied. One of the most important factors influencing the physical and mental condition of a worker and his or her ability to cope with work is the degree to which workers can recover from fatigue and stress at work. Recovery is the process that repairs the negative effects of strain or the period of time during which an individual's functioning returns to its prestressor level (Demerouti et al., 2012; Jansen et al., 2002). A clear way to recover energy is to take a break from activities that deplete energy resources. Moreover, for a break to result in recovery, people must utilize this time to engage in activities that reduce demands on personal resources and allow the opportunity for these resources to be recovered (Trougakos & Hideg, 2009). Jett and George (2003) defined the rest break as "planned or spontaneous suspension from work on a task that interrupts the flow of activity and continuity."

Breaks can be formally planned by organizational practices (e.g., coffee and lunch breaks) or informally instituted by workers themselves. It may be noted that the work preferences, related to timing and length of breaks, are not equal for everyone. For instance, some people may schedule breaks at regular intervals throughout the day, while others may take breaks at random times throughout the day and follow a configuration of seemingly unproductive days punctuated by a highly productive day (Jett & George, 2003). Rest periods involve multiple and important positive functions for the person being interrupted, including stimulation for the individual who is performing a job that is routine or boring, job satisfaction, sustained productivity, and time for the subconscious to process complex problems that require creativity. In addition, the regular breaks seem to be an effective way to control the accumulation of risk during the industrial shift. They are recommended to prevent the accumulation of risk of accidents during the activities supported, and results of laboratory tests and studies performed in the field strongly support these recommendations. Nonetheless, they can be potentially disruptive to the workflow and task completion because they can result in loss of available time to complete a task, a temporary disengagement from the task being performed, procrastination from performing a task, and reduction in productivity (Jett & George, 2003).

3.1 Breaks impact on human performance: well-being, recovery, and risk

Most research on breaks has focused on the long-term consequences of extensive breaks such as sabbaticals (Davidson, et al., 2010), vacations (Fritz & Sonnentag, 2006), weekends (Ragsdale, Beehr, Grebner, & Han, 2011; Fritz & Sonnentag, 2005), and evenings (Demerouti, Geurts, & Taris, 2009). While most studies on daily recovery focus exclusively on the engagement in off-job activities that may reduce fatigue and restore physiological and psychological readiness, little is known about recovery from short breaks that occur during the working day. The relatively few studies that directly address breaks indicate that people need occasional changes in the time of work or an oscillation between work and recreation, particularly when they are fatigued or working continuously for an extended period (Trougakos & Hideg, 2009; Jett & George, 2003; Dababneh et al., 2001). The lines of research typically examined focus on various aspects such as the frequency, timing, and length of breaks or activities undertaken during the rest period (doing physical exercises, socializing, napping).

The primary domain for exploring the benefits of within-day work breaks is ergonomics because of its role in preventing musculoskeletal problems, although systematic reviews suggest that there is only limited evidence of their effectiveness in this regard (Kennedy, Amick III, Dennerlein, Brewer, & Catli, 2009; Brewer et al., 2006).

Many studies have focused on computer-based tasks. Researchers in this area have focused on standard and micro breaks as a means to alleviate musculoskeletal discomfort and strain associated with prolonged or repeated office-related tasks. Galinsky et al. (2000), McLean et al. (2001), and Balci and Aghazadeh (2004) found positive effects depending on the time between rest breaks and musculoskeletal outcomes. In McLean's (2001) study, the authors examined the benefit of micro breaks by investigating myoelectric signal behavior, perceived discomfort, and worker productivity while individuals performed their usual keying work. Participants were randomly assigned to one of the three experimental groups: micro breaks at their own discretion, micro breaks at 20-min intervals, and micro breaks at 40-min intervals. It was determined, with p-value equal to 0.05, that micro breaks had a positive effect on reducing discomfort in all areas studied during computer terminal work, particularly when breaks were taken at 20-min intervals. Similarly, Balci and Aghazadeh (2004) investigated three different work-rest schedules (60-min work/10-min rest, 30-min work/5-min rest, 15/micro breaks four from each hour in addition to a 14-min break after 2 h) considering two types of task (cognitive task and data entry). The results indicated that the effect of the work-rest schedule was significant on various perceived discomfort categories and the performance of the participants, and the author suggested that the 15/micro break schedule is preferable to the longer and infrequent rest break schedules considering upper extremity discomfort, eyestrain, speed, accuracy, and performance of the participants.

Worker productivity takes advantage of short rest breaks. Balci and Aghazadeh (2004) reported that the performance in data entry tasks with the 15/micro break schedule was 18% higher than the 30-min work/5-min rest schedule and 24% higher than the 60-min work/10-min rest schedule. Henning et al. (1997) and Van de Heuvel et al. (2003) combined physical exercises with breaks in order to study their effect on human performance. Productivity growth and discomfort reduction were achieved with two 5-min rest breaks with exercises in addition to the normal rest breaks both in the mid-morning and mid-afternoon during an 8-h work day. Exercise breaks also improved workers' well-being and eye, leg, and foot comfort (Henning et al., 1997).

The impact of frequent short rest breaks on productivity and well-being has also been investigated in the manufacturing field. Dababneh et al. (2001) tested two rest break policies in a meat-processing plant. Results showed that neither of the two experimental rest break schedules had a negative effect on production, and the 9-min break schedule improved discomfort ratings for the lower extremities.

Surprisingly, a small number of studies have examined the function of recovery both at work and home. The recovery experience refers to the degree to which individuals perceive that the breaks they take help them to restore energy resources. Demerouti et al. (2012) examined the recovery experience after breaks at work and psychological detachment from work when being at home by investigating the role of recovery at work in the process of energy replenishment. The authors distinguish between two types of recovery: recovery during work, which takes place when the stressor factors are present, and recovery after work, which occurs when the stressor factors are absent. All examined relationships are summarized in Figure 3. Results of the multilevel analysis indicated that recovery at work and detachment from work moderated the relationship between flow (specifically, the enjoyment component) and after-work energy. An association between need for recovery from work, fatigue, and psychological distress in the working population was also observed in Jansen et al. (2002). Need for recovery was higher in men than in women and in the higher age groups, as others have found (Mohren, Jansen, & Kant, 2010).

Evidence has recently highlighted that the beneficial effects of rest breaks on strain and mood are influenced by the nature of the activity undertaken during the breaks (Tucker & Folkard, 2012). Experimental field studies found that rest breaks were more likely to enhance subsequent mood if they involved respite activities (e.g., napping, relaxing, socializing) rather than chores (e.g., working with customers, running errands, and work preparation) (Mathiassen, Hallman, Lyskov, & Hygge, 2014; Tucker & Folkard, 2012).

Several studies have examined the impact of rest breaks during a shift on injury or accident risk (Tucker & Folkard, 2012; Folkard & Lombardi, 2006; Tucker, Lombardi, & Smith, 2006; Folkard & Tucker, 2003; Tucker et al., 2003). They agree that risk is reduced in the first half-hour following a rest break and that this effect is similar across all three shifts. The number of injuries within each of the four 30-min periods between breaks was calculated, and the risk in each 30-min period was expressed relative to that in the first 30-min period immediately following the break. Results are shown in Table 1, and it is clear that injury risk rose substantially and approximately linearly between successive breaks such that risk had doubled by the last 30-min period before the next break. The trends over subsequent half-hours varied, possibly reflecting the extent to which the work was either self-paced or machine paced. It would therefore appear that the beneficial effects of rest breaks may be relatively short lived in at least some work environments.

Time on task (min)					
	0-29	30-59	60-89	90-119	Total
Period					
1	23 (13%)	41 (23%)	50 (29%)	61 (35%)	175
2	28 (16%)	30 (18%)	47 (28%)	65 (38%)	170
3	35 (19%)	43 (24%)	50 (28%)	53 (29%)	181
All periods	86 (16%)	114 (22%)	147 (28%)	179 (34%)	526
Relative risk	1 (reference)	1.33	1.71	2.08	

Table 1: Frequency (% of total per period) of accidents per half-hour for each work period and relative risks for all periods combined (Tucker et al., 2003).

Tucker et al. (2006) analyze the trend in work-related injuries in relation to the timing of rest breaks in two separated studies. Risk increased from the first to the second half-hour of continuous work and then remained relatively constant in the third half-hour. In some of the data, there was also a decrease in risk in the period leading up to the end of a work period. There was a sharp decline in reported injuries toward the very end of a shift, but otherwise, the observed trends did not differ between successive periods of continuous work or among morning, afternoon, and night shifts. However, no direct epidemiological evidence exists for the effect of rest breaks on the trend in risk as a function of time-on-task.

3.2 Break scheduling problems

Break scheduling problems emerge in many working contexts where rest period is indispensable due to features of the tasks to be performed. These features include the requirement of high concentration during extended periods of time, continuous work in front of computer monitors, or other monotonic and exhaustive activities. Typically, break scheduling problems arise in call centers, security checking, or assembly lines.

In literature, the break scheduling problems have been hardly addressed on their own, but they are part of the most famous shift scheduling problem, which has received a lot of attention in the operations research literature. Shift scheduling problems, in fact, deal with the assignment of employee starting and finishing times, and possibly the placement of relief and meal breaks within each shift in order to maximize work output per unit time or minimize the costs of assigning an employee to alternative shifts (Rekik et al., 2010; Aykin, 1996). The validity of approaches to scheduling breaks development over the years has been limited by the assumption of optimality of complete recovery, exclusion of rest break penalties, or restriction to a single break (Bechtold et al, 1984).

The first work-rest model was developed by Eilon in 1964 to determine the optimal length and placement of one break over a finite time horizon for a single employee for a general work rate *r (t)*, which was a decreasing function of time. Gentzler, Khalil, and Sivazlian (1977) developed a multirest break model for an infinite time horizon based on the assumption that full recovery was optimal. Starting from this incorrect assumption and assuming linear performance decay during work and linear recovery of work-rate performance potential during rest, the selection of the optimal number, duration, and placement of rest breaks over a single finite time horizon became a mixed-integer quadratic programming problem in Bechtold et al. (1984). This model was applied in experimental settings observing productivity improvements of around 8% for a mental task and around 3% for a physical task. Results suggested that it is likely that breaks of a given length may be more effective if taken earlier in the time horizon than when they are evenly spaced. Bechtold and Thompson (1993) extended this earlier research by considering the choices of placement for and during a single rest period that must be taken simultaneously by all employees in a work group through an appropriate model formulated as a mixed-binary, cubic programming problem. Aykin (1996) considered a more general shift scheduling problem with multiple breaks and disjoint break windows and developed an integer programming model for optimal shift scheduling with multiple rest and lunch breaks and break windows, which reduces the number of variables compared to the set-covering formulation, typically used in the scheduling problems. Rekik et al. (2010) extended this formulation incorporating two other forms of flexibility: fractionable breaks and work stretch duration restrictions. This provides the possibility of fixing only the total duration of breaks that must be given within a shift without specifying which break length comes in which position. Experimental results prove that using fractionable breaks may yield, for some instances, a considerable saving of workforce.

In addition to the exact methods, the meta-heuristics such as min-conflicts-based local search algorithm, or memetic algorithm have been presented in literature for breaks scheduling. Musliu et al. (2009) proposed a memetic algorithm to obtain solutions of improved quality for the break scheduling problem for supervision personnel. This algorithm consists of the selection, crossover, and mutation of three standard operators and is hybridized with a min-conflicts search. Initial solutions are constructed with break patterns already fulfilling constraints representing labor rules and ergonomic criteria. For every iteration, the genetic operators generate a pool of different solutions from the previous generation, and the best solutions are further optimized by the local search procedure. Wild and Musliu (2010) improved the previous method by proposing a new memetic representation, a new crossover and selection operator, and a penalty system that helps to select memes that have a better chance to be improved by a local search. Di Gaspero et al. (2010) devised a hybrid strategy that combines a local search method for determining the shifts with a constraint programming model for assigning breaks. This model has shown to be very practical for the local search to find legal break assignments that optimize over/under staffing.

Quantitative models for optimal rest period scheduling were developed with work rate function as basic component. The work rate function defines the performance level from the end of one rest period to beginning of the next rest period, representing the individual fatigued state. The processes of works output decay during work periods and recovery of work rate potential during rest breaks are modelled as linear functions of time (Bechtold et al., 1984).

None of existing methods considers human reliability in assessing worker performance due to the complexity of HRA approaches, as underlined in section 2, and given the difficulty of integrating this type of modeling in an exact algorithmic or heuristic technique. Furthermore, many of the studies in the literature have addressed the break scheduling problem only from the point of view of productivity. They do not address the problem of break management with regard to the quality aspect, namely the impact of human errors on the system performance in terms of quality of the performed activities (e.g. non-compliant items and reworking). The impact of breaks, in fact, was investigated with respect on the loss of productivity, due to the decrease of work rate, without considering the effect on the human error probability.

4 SHERPA model for break scheduling assessment

Despite the impact of human factors in industrial systems and the development of numerous HRA and breaks scheduling approaches in literature, they have still many limitations, as previously seen.

Starting from the HRA shortcomings, SHERPA has been developed for predicting the probability of human error for a given scenario in every type of industrial system or other type of working contexts (Di Pasquale et al. 2015a ,b). It is designed for HRA, and unlike many existing HRA methods that are deeply qualitative and include excessive levels of detail for many assessments, SHERPA focuses on the quantitative aspect to obtain a significant numerical result in terms of HEP. Human reliability is estimated as a function of the performed task, influencing factors (PSFs), and time worked, with the purpose of considering how reliability depends on the task and working context as well as on the time that the workers have already spent at their work. Knowing the HR distribution allows to intervene from the perspective of reducing errors with re-design tasks or other interventions such as the management of the worker's psychophysical recovery through appropriate break configurations.

The proposed HRA-based model is addressed to the break scheduling problems through the hypothesis that breaks allow the mental and physical recovery and lead to improvements of human reliability. The positive break impact on human reliability is a function of break time, location of break during the shift, recovery speed and type of performed activities. Rest breaks have also a negative aspect due to increased idle time that corresponds to a decrease of productivity. For this reason, SHERPA is based on an economic model, that allows to assess both positive and negative break effects and to compare their impact on the system performance, considering the cost of lost production due to break and the quality costs related to operator errors. The main SHERPA focus is the modeling and simulation of rest breaks in order to assess the impact of different work-break policies, with several placement and duration of breaks, on human performance (HEP and recovery after the break) and the overall system performance in terms of percentage of compliant performed tasks and economic results (e.g. profits, revenues, quality costs, rework costs and break costs).

The model can be adapted to alternative set of constraints (minimum number of breaks and minimum time guaranteed by legislation or internal union agreements, maximum hours of continuous work and other possible constraints), assigned in the initialization phase of the system as inputs. SHERPA can then evaluate the effect of every work-rest policy, defined as acceptable for the system under consideration, with the aim of identifying the best configuration among those possible.

The model was developed based on the review of literature in HRA and rest breaks policy. Three HRA elements converge into the model: the task classification proposed by human error assessment and reduction technique (HEART) method (Kirwan, 1996), the PSFs analysis of the SPAR-H method (Gertman et al., 2005) and the dynamic implementation using computer simulation (Boring, 2007). The operator's recovery and the breaks policy were based instead on the state of the art previously presented.

The theoretical framework, described in the following sections, has been implemented as simulation template in Arena 14.0©. It allows a lot of different scenarios to be simulated easily without consuming a lot of time by changing the type of activity, the influencing factors, and especially the break configurations. In this paper, the SHERPA model, previously presented in Di Pasquale (2015a, b), is described in depth with attention to the management of breaks scheduling and worker's recovery. The next section describes the SHERPA theoretical framework and the simulation logic.

4.1 Notations

The following notations will be used in this paper:

$\mathrm{HEP_n}$	nominal human error probability
$\mathrm{HEP_c}$	contextual human error probability
HR	human reliability ($1 - \mathrm{HEP_c}$)
k, β, and α	shape and scale of Weibull distribution
τ	length of the transitional phase of human adaption
$\mathrm{PSF_{composite}}$	performance shaping factors composite
$\mathrm{r_p}$	recovery factor
ω	recovery rate
R	Revenues
P	price/value added of the processing
$\mathrm{CF_{STD}}$	standard fixed costs
$\mathrm{CV_{STD}}$	standard variable costs
T_c	processing time
$\mathrm{C_r}$	reworking costs
$\mathrm{c_b}$	rest break costs
$\mathrm{T_b}$	rest break time
T_r	reworking time
$\mathrm{P_r}$	reworking probability

4.2 Theoretical framework and simulation template

The SHERPA theoretical framework has been described with the technique IDEF0, which is a widely-used technique for the structured analysis and design of systems developed through the Air Force's integrated computer aided manufacturing program (Presley & Liles, 1995). The four elements (inputs, outputs, controls, resources) to the IDEF0 functional model are shown in Figure 4, where the activity box is the SHERPA model. The inputs are represented by the arrows flowing into the left-hand side of the activity box and they are the entities, which equally represent the pieces to be processed or the physical/mental activities to be performed by the employee that can be performed or diagnosed.

The model reproduces the employee's work during a whole shift, quantifying the reliability and error probability that moved on the outputs of the system, represented by arrows flowing out the right-hand side of the activity box. SHERPA determines as outputs the number of compliant, noncompliant, and rework entities. To date, as first approximation, the model directly links the contextual HEP to the number of noncompliant entities. The concept of quality defects and noncompliant entities is not limited to manufacturing processes, but extends to a wider range of working environments, ranging from services to medical field. Further outputs are the HEP distribution and the economic results. The arrows flowing into the top portion of the box represent constraints or controls on the activities: the HRA and the recovery principles; the influencing factors (PSF), namely the contextual factors and the physical and mental employee conditions; and the assigned work-rest policy. Finally, the resources, represented by arrows flowing into the bottom of the activity box, are the mechanisms that carry out the activity. The main activity box has been decomposed into more detailed levels of analysis, through the four sub-models shown in Figure 5 and analyzed in detail in the next sections. The four sub-activities (entities entry, HR quantification, process simulation, entities exit) are supported by the operating logic shown in Figure 6.

The starting analytical basis for the assessment of human errors in SHERPA is the determination of the nominal HEP, followed by quantification of PSFs influences and identification of contextual HEP. The worker's reliability is used in a generic work process simulation to indicate the probability that the worker will be able to carry out activities without errors in a specific scenario. Different scheduling of breaks can be assigned and can be simulated in the shift, considering that a break determines the worker's recovery and the consequent increase in reliability. As explained in detail later, the proposed model can manage a pool of break configurations, which are included into two main groups: no break in the shift (continuous working) or fixed breaks policy (several timing and length of rest period).

The performances of every given scenario are expressed in the first instance in terms of nonconformity percentage of the entity in output. This value, integrated with many other available outputs, allows a clear and direct assessment of how the system reacts to change in the given break scheduling, as well as to change in environmental and psychophysical conditions (Di Pasquale, Miranda, Iannone, & Riemma, 2015c).

4.2.1 Entities entry

The entities in entrance represent many working contexts because they can equally simulate a work piece, a document to be drafted, or in general, a task to be performed. The model manages in the same manner all the typologies, recognizing in the case of product mix the needs of setup. In this phase, the model follows the flowchart in Figure 7. A set of technical data (type of performed task, processing time, setup time, time for rework) and economic data (product price, fixed and variable costs) is allocated to each entity in the first step.

4.2.2 Human reliability quantification

The second phase is addressed to the nominal and contextual HEP quantification, which is the first step in any HRA approach, as reported in Figure 8. The flowchart illustrates the process of HR quantification and its main phases. The nominal and contextual HEP and the PSF composite are quantified for each entity and are representative of each performed task, as described hereafter.

The nominal HEP, independent of the presence of influencing factors, is a function of the performed activity and worked time. The Weibull probability distribution is presented by Giuntini (2000) as the best distribution to describe the error probability and to characterize the human reliability process. It is adapted in the proposed model to take into account the natural process of adaptation for a typical human for a given operation that results in a lower reliability in the initial part of the shift as follows:

$$\begin{cases} HEP_{nominal}(t) = 1 - k \cdot e^{-\alpha \cdot (1-t)^{\beta}} \quad \forall\, t \in [0; \tau] \\ HEP_{nominal}(t) = 1 - k \cdot e^{-\alpha \cdot (t-1)^{\beta}} \quad \forall\, t \in \,]\tau;\, \infty[\end{cases} \tag{2}$$

where t is the time worked by an employee; k, β, and α change the scale and shape of the curve for the six generic tasks used in the model; and τ is the length of the transitional phase of human adaption. SHERPA uses six general categories to classify the type of performed task, derived by the HEART (Kirwan, 1996), and each of them is connected to an appropriate probability distribution that describes nominal HEP as a function of time (Di Pasquale, et al., 2015b). The categories shown in Table 2 can represent a wide range of work activities from simple to more complex ones, and from ones with a very high error rates to those more reliable, thanks to the presence of automatic systems of supervision.

The working context and employee state in SHERPA are taken into account through the PSFs of the SPAR-H method. While many HRA methods have often proposed a large number of PSFs, even as many as fifty, SPAR-H attempts to provide a reasonable coverage of the influence spectra of human performance in a reasonable minimum number of PSFs.

Table 2: Coefficient values for the six generic tasks.

Generic task		Limitations of unreliability for operation	k	α	β
1	Totally unfamiliar	35% ÷ 97%	0.65000	0.1660762	1.5
2	Complex task requiring high level of comprehension and skill	12% ÷ 28%	0.88000	0.0108352	1.5
3	Fairly simple task performed rapidly or given scant attention	6% ÷ 13%	0.94000	0.0041785	1.5
4	Routine, highly-practiced	0.7 ÷ 4.5%	0.99300	0.0021068	1.5
5	Completely familiar, well-designed, highly practiced, routine task	0.008% ÷ 0.9%	0.99920	0.0004838	1.5
6	Respond correctly to system command even when there is an augmented or automated supervisory system	0.0001% ÷ 0.09%	0.99991	4.813*10^-5	1.5

The eight PSFs are the following: available time; stress; complexity; experience and training; procedures; cognitive ergonomics; fitness for duty; and work process. The decision to use only eight PSFs in SPAR-H, followed also in the proposed model, is based on a review of the available HRA methods and the behavioral sciences (Boring, 2010). Nominal HEP is thus modified by these eight PSFs using the following adjustment factors (Blackman, Gertman, & Boring, 2008; Gertman et al., 2005):

$$HEP_{contextual}(\mathrm{t}) = \frac{HEP_{nominal}(\mathrm{t}) \cdot PSF_{composite}}{HEP_{nominal}(\mathrm{t}) \cdot (PSF_{composite} - 1) + 1} \tag{3}$$

where $\mathrm{PSF}_{\mathrm{composite}}$ is calculated as

$$PSF_{composite} = PSF_1 \times \ldots \times PSF_x \times \ldots \times PSF_8 \tag{4}$$

where PSf_x is the assigned multiplier for each PSF as reported in Di Pasquale et al. (2015b).

Some PSFs, such as complexity, stress, and working processes, are composed of several subfactors, introduced to make the modeling closer to reality. In this case, a submultiplier is assigned to each subfactor and the overall PSF multiplier is quantified through weighted average of submultipliers.

4.2.3 Process simulation

The third submodel performs the worker's simulation, taking into account the features of the process, the HEP, and the assigned breaks scheduling. SHERPA can manage two different rest breaks policies:

- no break in the shift (continuous working);
- fixed breaks (several timing and length of rest period).

The operating principles are displayed in the flowchart (Figure 9), where the breaks policies are represented. The absence of breaks (yellow box) corresponds to the mere reproduction of the process. The activities are simulated based on the model inputs, technical and economic data (processing and setup times, number of entities, workplace conditions, and many others), and the corresponding HR distribution, taking into account the hours of continuous work already carried out by the worker. The contextual HEP value, output from this block, consents to quantify the noncompliant percentage in the next phase and evaluate the overall worker performance.

The fixed break introduction (red box) involves the management of the worker's physical and mental recover and of the reliability increase. The worker's recovery (gray box) is modeled as a function of the break length and of the type of activity carried out. The recovery factor (r_p), that takes the Wright learning curve as a reference, is expressed by the exponential function:

$$r_p = e^{-\omega T_b} \tag{5}$$

in which T_b is the break length (in hours) and ω is the recovery rate. This coefficient has been hypothesized for four general categories, which describe different working activities listed in Table 3 and has been modified and improved compared to the previous estimate (see Di Pasquale, 2015b) on the basis of the literature review discussed in the Section 3.1. The recovery index for the four cases has been quantified by imposing, as a boundary condition, that the maximum recovery is obtained for r_p equal to 0.1 by setting this rate at three levels (slow, medium, and fast). In this way, the maximum break time is limited: in fact, the rp curve tends asymptotically to come to a null value with increasing break time; full recovery would be obtained in correspondence to a break of infinite time. Below the value of rp of 0.1, it has been assumed that the break not have substantial effects on the recovery of the operator.

Table 3: Types of activities and corresponding parameters for the optimal allocation of the breaks.

Activity	Recovery rate (ω)		
	Slow	Medium	Fast
Sedentary activities (office, laboratory)	2.76	4.61	13.82
Activity light, standing (laboratory, light industry)	2.51	3.95	9.21
Medium activity, standing (work machines)	2.30	3.45	6.91
Activities heavy (heavy work machines)	1.97	2.76	4.61

The HR improvement, due to the rest period, is modeled considering that the human reliability curves after a break is reported to a previous moment with a lower level of HEP and this new distribution of nominal HEP is a function of the length of same break. The recovery factor impact on the nominal HEP distribution is as follows:

$$HEP_{nominal}(t) = 1 - k \cdot e^{-\alpha \cdot (T \cdot r_p - 1)^{\beta}} \tag{6}$$

where T is the time in which the operator resumes its activity after the break and rp represents the level of recovery, the two parameters α and β change the scale and shape of the curve for each generic task.

Figure 10 shows the error probability curves of an 8-h shift in two given scenarios, which display action mechanism of the breaks on reliability curves. In the first case, a break of 20 min is assigned to half shift and it allows the almost full recovery, decreasing the average HEP. In the same way, four breaks of 5 min, distributed in the shift, modify the average human reliability. The impact of the break length on the worker's recovery is evident comparing the two HEP curves: a longer break (20 min) leads to higher recovery than shorter breaks (5 min). For the fixed breaks simulation, the model takes into account the exact break window and then it recalculates the nominal HEP before performing the processing phase.

4.2.4 Entities exit

The main SHERPA outputs are compliant, noncompliant, and rework entities. These categories are derived from the forecast of HEP on the basis of the performed activity of the period when the process is carried and of the contextual and individual conditions. As shown in the flowchart (Figure 11), each entity in the output from the system receives the compliant percentage and function of the error probability to overturn the human performances on the system ones. The reworking entails an increase of the processing time, as in Figure 11. It is possible to evaluate the economic results after the simulation is performed. The profit per unit is given by

$$R = (HR + HEP \cdot P_r) \cdot P - CF_{STD} - CV_{STD} - HEP \cdot C_r \cdot P_r - c_b \cdot T_b \tag{7}$$

where HR is the operator reliability; P is the item price; HEP is the probability of failure (1-HR); CF_{STD} is the standard fixed cost; CV_{STD} is the standard variable cost; P_R is the probability of recovery; C_R is the cost of recovery; cb is the cost of breaks per minute; and Tb is the break time in minutes. The break cost per minute is related to the loss due to the failure current work piece. It is therefore expressed as

$$c_b = \frac{((HR + HEP \cdot P_r) \cdot P - CV_{STD} - HEP \cdot C_r \cdot P_r)}{T_{total}} \tag{8}$$

where T_{total} is the total time of processing in minutes that considers the time increment linked to rework:

$$T_{total} = (HR + HEP) \cdot T_c + HEP \cdot P_r \cdot T_r \tag{9}$$

where T_c is the processing time; T_r is the time required for the reworking, defined as percentage increase of the processing time; and P_R is the probability of recovery.

5 CASE STUDY: An illustrative example

In the present section, a numerical example is presented adopting the proposed approach for the breaks scheduling assessment. To illustrate the SHERPA operating, a manual assembly process was simulated as a case study, involving a single 8-h shift for 230 days per year. The simulated assembly task is mixed-model with two different items (P1 and P2) with similar assembly processes and with random arrival sequences based on the fixed production mix (65% P1 and 35% P2). The assembly operation was performed with processing times reported in Table 4 and characterized by a triangular distribution, with vertices corresponding to the mean ±10%. The economic parameters are set according to what is shown in Table 4.

The SHERPA template, integrated in a specific Arena model, was set to reproduce an operator with high experience (PSF experience = high level) and in good physical fitness (PSF fitness for duty = nominal level) involved in moderately complex tasks. The PSFs for the context have been chosen to represent approximately the actual conditions in the assembly plant: available time and work processes have been imposed at the nominal level while stress, procedures and ergonomics at the moderate/high level.

Table 4: Features of simulated items.

Features	P1	P2
Productive mix	65%	35%
Mean Processing time (min)	5	7.5
Setup time (min)	0.5	0.5
Price/added value (€)	20	25
Fixed standard cost (€)	3.76	5.64
Variable standard cost (€)	9.84	13.7

The template, as implemented, investigates the performance of different work break configurations and it has been applied in different scenarios changing the simulation parameters in Table 5.

Table 5: Simulation parameters.

Parameters	Levels	Values
Recovery rate	3	Slow, Medium, Fast
Break Length (min)	3	20, 25, 30
Number of breaks	5	0, 1, 2, 3, 4
Reworking time (Tr)	2	+15%, +30%
Reworking probability (Pr)	2	30%, 60%

Every break configuration was simulated for the three different recovery rates (slow, medium, and fast), for two different reworking probabilities (30% and 60% of the noncompliant items) and for two reworking times, which involve an increase of processing time equal to 15% and 30%. Without considering the four reworking classes, Table 6 shows the list of the simulated scenarios in order to have a clearer and more immediate understanding of them.

Table 6: Simulated scenarios.

		RECOVERY RATE								
Tr= $x\%$		Slow			Medium			Fast		
Pr= $x\%$		Total Breaks Length			Total Breaks Length			Total Breaks Length		
		20	25	30	20	25	30	20	25	30
Number of breaks	1	S-20-1	S-25-1	S-30-1	M-20-1	M-25-1	M-30-1	F-20-1	F-25-1	F-30-1
	2	S-20-2	S-25-2	S-30-2	M-20-2	M-25-2	M-30-2	F-20-2	F-25-2	F-30-2
	3	S-20-3	S-25-3	S-30-3	M-20-3	M-25-3	M-30-3	F-20-3	F-25-3	F-30-3

	4	S-20-4	S-25-4	S-30-4	M-20-4	M-25-4	M-30-4	F-20-4	F-25-4	F-30-4
No breaks		(S-M-F) 0-0								

Two types of work-rest schedule have been introduced: a single break in half shift or more breaks distributed at different times on the entire work shift. For each break configuration, the overall rest period length was considered respectively equal to 20/25/30 min. In the case of distributed breaks, the following distributions were hypothesized:

- Scenarios with 20 min of break:

Number of breaks	Length (min.)	Interval (min.)
2	10-10	180-120-120
3	6-8-6	150-90-90-90
4	5-5-5-5	132-72-72-72-72

- Scenarios with 25 min of break:

Number of breaks	Length (min.)	Interval (min.)
2	12.5-12.5	180-120-120
3	8-9-8	150-90-90-90
4	6-6-7-6	132-72-72-72-72

- Scenarios with 30 min of break:

Number of breaks	Length (min.)	Interval (min.)
2	15-15	180-120-120
3	10-10-10	150-90-90-90
4	7-8-7-8	132-72-72-72-72

In summary, the case study has been applied in 148 different scenarios in order to show how effective solutions for the break scheduling problem can be found with the proposed simulator.

5.1 Simulation results

Results for every scenario consist of total value of compliant and noncompliant items, their respective percentages, mean values of the HEP context, as well as the economic results in terms of profit, revenue, scraps costs, rework costs, and breaks costs. Table 7 shows the average HEP for every scenario. These values reflect the chosen case study and they are a function of the performed assembly task as well as of the supposed individual and contextual factors. In addition to the scenarios defined, additional scenarios were simulated in the absence of breaks for every reworking class. The human error probabilities, reported in Table, were significantly lower than those to the reference case in the absence of breaks because of the presence of operator's psychophysical recovery.

Table 7: Average HEPs for the simulated scenarios.

		RECOVERY RATE								
Tr = +15% **Pr = 30%**		Slow			Medium			Fast		
		Total Breaks Length			Total Breaks Length			Total Breaks Length		
		20	25	30	20	25	30	20	25	30
Number of breaks	1	12.88%	12.20%	11.65%	11.83%	11.28%	11.19%	11.35%	11.28%	11.19%
	2	12.85%	12.06%	11.40%	11.57%	10.78%	10.18%	9.66%	9.61%	9.55%
	3	12.88%	12.09%	11.40%	11.55%	10.72%	10.09%	9.36%	8.88%	8.82%
	4	12.97%	12.13%	11.45%	11.61%	10.74%	10.08%	9.28%	8.67%	8.43%
No breaks		17.86%								

		RECOVERY RATE								
Tr = +15% **Pr = 60%**		Slow			Medium			Fast		
		Total Breaks Length			Total Breaks Length			Total Breaks Length		
		20	25	30	20	25	30	20	25	30
Number of breaks	1	12.89%	12.19%	11.64%	11.82%	11.28%	11.19%	11.35%	11.28%	11.19%
	2	12.85%	12.06%	11.39%	11.56%	10.78%	10.18%	9.67%	9.61%	9.55%
	3	12.88%	12.10%	11.40%	11.54%	10.72%	10.08%	9.36%	8.87%	8.83%

	4	12.96%	12.13%	11.45%	11.60%	10.74%	10.07%	9.29%	8.68%	8.43%
No breaks						17.84%				

		RECOVERY RATE								
Tr = +30%		Slow			Medium			Fast		
Pr = 30%		Total Breaks Length			Total Breaks Length			Total Breaks Length		
		20	25	30	20	25	30	20	25	30
Number of breaks	1	12.90%	12.19%	11.64%	11.82%	11.27%	11.20%	11.36%	11.27%	11.20%
	2	12.85%	12.05%	11.39%	11.56%	10.79%	10.18%	9.67%	9.61%	9.55%
	3	12.88%	12.08%	11.40%	11.53%	10.72%	10.07%	9.35%	8.86%	8.83%
	4	12.97%	12.12%	11.44%	11.59%	10.74%	10.08%	9.28%	8.68%	8.43%
No breaks						17.88%				

		RECOVERY RATE								
Tr = +30%		Slow			Medium			Fast		
Pr = 60%		Total Breaks Length			Total Breaks Length			Total Breaks Length		
		20	25	30	20	25	30	20	25	30
Number of breaks	1	12.86%	12.19%	11.62%	11.80%	11.26%	11.19%	11.35%	11.26%	11.19%
	2	12.84%	12.04%	11.38%	11.54%	10.78%	10.16%	9.66%	9.60%	9.54%
	3	12.87%	12.07%	11.39%	11.52%	10.71%	10.08%	9.36%	8.88%	8.82%
	4	12.93%	12.11%	11.44%	11.58%	10.73%	10.07%	9.23%	8.67%	8.44%
No breaks						17.80%				

As described in Section 4.2.4., the profits, related to the correct execution of each task, depend on the revenues of the compliant items, the scraps costs (fixed and variable unit costs), the costs of the reworking items (rework costs), and finally the breaks costs that stand for lack of production. Table 8 reports the profits for the all the configurations which will be analyzed in detail hereinafter.

Table 8: Profit in euros for the simulated scenarios.

		RECOVERY RATE								
Tr = +15%		Slow			Medium			Fast		
Pr = 30%		Total Breaks Length			Total Breaks Length			Total Breaks Length		
		20	25	30	20	25	30	20	25	30
Number of breaks	1	64,497	64,367	63,794	67,674	66,825	64,971	68,763	66,825	64,971
	2	65,210	64,494	62,992	68,212	67,794	67,229	73,051	71,293	67,946
	3	65,399	64,163	64,060	67,620	67,908	66,888	72,730	72,719	70,521
	4	63,846	64,103	63,378	67,621	67,457	67,929	74,235	72,942	70,857
No breaks						61,339				

		RECOVERY RATE								
Tr = +15%		Slow			Medium			Fast		
Pr = 60%		Total Breaks Length			Total Breaks Length			Total Breaks Length		
		20	25	30	20	25	30	20	25	30
Number of breaks	1	76,861	75,207	73,646	79,005	76,699	74,131	79,754	76,699	74,131
	2	77,272	75,181	74,399	79,378	77,650	76,257	81,344	79,439	77,052
	3	77,249	75,163	74,159	79,415	77,363	76,055	82,513	80,214	78,101
	4	76,597	75,755	74,047	79,228	77,680	76,459	82,447	81,186	78,943
No breaks						79,615				

		RECOVERY RATE								
Tr = +30%		Slow			Medium			Fast		
Pr = 30%		Total Breaks Length			Total Breaks Length			Total Breaks Length		
		20	25	30	20	25	30	20	25	30
Number of breaks	1	64,191	63,365	63,221	67,420	66,371	63,871	68,158	66,371	63,871
	2	63,489	63,358	63,648	67,234	66,677	66,009	72,251	70,499	68,158
	3	64,041	64,226	63,253	67,713	67,638	66,444	73,294	72,664	69,257

	4	64,197	63,872	64,087	67,375	67,571	67,598	73,904	74,328	70,941
No breaks						59,703				

		RECOVERY RATE								
Tr = +30% **Pr = 60%**		Slow			Medium			Fast		
		Total Breaks Length			Total Breaks Length			Total Breaks Length		
		20	25	30	20	25	30	20	25	30
Number of breaks	1	75,569	74,906	72,800	77,602	75,861	74,707	78,366	75,861	74,707
	2	75,964	75,010	73,690	78,072	77,110	75,005	81,562	79,010	76,054
	3	76,105	75,666	72,772	78,363	77,026	75,168	82,347	80,257	77,552
	4	75,984	75,977	73,265	78,595	76,784	75,077	82,328	80,867	77,606
No breaks						78,347				

5.2 Discussion

The purpose of this study is the evaluation of impact of different policies on human reliability and system performance for an assembly process. The reliability evaluation involves three significant aspects associated with the impact of recovery rate, breaks length, and configurations. The decrease of worker error probability in the simulated scenarios, in fact, derives from the break length and the recovery rate and it is underlined graphically in Figure 12. There is a statistically significant interaction between the effects of recovery rate and break time on the HEP; therefore, the effect on the mean outcome of a change in one factor depends on the level of the other factor. The vertical bars in the graphs indicate the level of confidence at 95%.

The human unreliability is a function of the operator's recovery rate through equation (6), as previously explained in Section 4.2.3. With equal break lengths, in fact, a slower recovery rate leads to higher values of HEP. The recovery rate is an inherent feature of the worker that depends on several elements, such as the age (Mohren et al., 2010), and even if in a limited manner, it can be influenced by the regenerating activities during the same break, e.g., specific physical exercises (Balci & Aghazadeh, 2004; Van de Heuvel et al., 2003). The increase of total break time in the shift, instead, improves human reliability because the worker has more time to rest and receive a greater psychophysical recovery. This increase is naturally stronger in the case of slow recovery rate than that fast, because in this last case, a shorter time for an adequate recovery is enough. The last assessment is linked to the effect of several work-break configuration in the shift (Figure 13). It is evident that the four work-rest policies impact differently on the worker reliability according to the rate of recovery. The HR improvement is much more stringent for the fast recovery rate, where the single break in half shift is less effective and significantly worse compared to the other three configurations, which exploit the distribution of shorter breaks over 8 h to their advantage. The work-rest policies with three or four breaks in the shift allow the worker more rest moments, increasing its average reliability. These benefits are less marked in the case of medium recovery rate and almost insignificant when the recovery rate becomes slow. This can easily be justified with a propensity to longer pauses that allow a greater recovery for the operator.

The previous evaluations were carried out without discrimination on the reworking class (reworking time and reworking probability) since this has no impact on the HEP. In the economic evaluations, however, the reworking class must be taken into account due to its significant effect on the profits. Comparing Table 7 and Table 8, it is evident that when reworking class changes, the HEP value remains unchanged while the profits vary greatly. This effect can be easily justified, considering that the rework has no impact on the human reliability distribution, but it influences the number of compliant items of the system that generate higher profits. For this reason, the scenarios were evaluated separately considering the different reworking classes and recovery rates in order to assess the economic impact of different break configurations. Figure 14 reports the profits for the scenarios with rework probability equal to 30% recovery and rework time equal to 30% for the three recovery rates. It is evident that the one-break configuration is always less advantageous compared to three or four distributed breaks in terms of economic performance. Unlike the HEP trend, the increase of the total length does not always have an improving effect on profit and the economic results only partially reflect the previous HR assessments.

Table 9 lists the economic results in the case of reworking time and probability equal to 30% in average conditions of recovery. The best results for each performance parameter are underlined. It is evident that the best economic performances do not correspond in the same order with the best reliabilities. This result derives from the combination of the economic impact of break times and break configurations. The positive HR variations related to the increase of the number and the length of breaks involves an improvement in the rate of quality of the processing and consequently a lower cost of scraps, while the increase of the break time determines a clear rise of the breaks costs. As described in Section 4.2.4, the break costs represent the costs of lost production time; naturally, the transition from 20 to 30 min increases the amount of products not manufactured and the break costs, and this is reflected in a reduction of global revenues, which do not result from a deterioration in the quality of work, but only by the reduction of the total worked hours.

Table 9: Details of the economic performance.

SCENARIO		PERFORMANCES					
Break time	**No. of breaks**	**Profits (€)**	**Revenues (€)**	**Scraps costs (€)**	**Rework costs (€)**	**Breaks costs (€)**	**HEP %**
20	1	67,420	96,936	22,121	633	6,762	11.82%
20	2	67,234	96,749	22,086	634	6,795	11.56%
20	3	67,713	96,997	21,855	630	6,799	11.53%
20	4	67,375	96,850	22,060	624	6,791	11.59%
25	1	66,371	96,131	20,597	624	8,540	11.27%
25	2	66,677	96,194	20,317	584	8,615	10.79%
25	3	67,638	96,458	19,604	589	8,626	10.72%
25	4	67,571	96,520	19,742	583	8,623	10.74%
30	1	63,871	95,306	20,560	615	10,261	11.20%
30	2	66,009	95,705	18,670	571	10,454	10.18%
30	3	66,444	95,849	18,352	578	10,475	10.07%
30	4	67,598	96,336	17,731	533	10,473	10.08%

Being the obtained profits strongly dependent on the economic parameters, a further analysis was carried out with the following changes on the reference case:

- Price/added value: ±20%;
- Fixed standard cost: ±50%;
- Variable standard cost: ±20%.

Figure 15 shows the profits for the new six scenarios obtained modifying such parameters according to the OFAT (One Factor At a Time) analysis technique. The effects of these changes belong to two distinct classes of result: growth and the reduction of the profit per unit. On one side, the reduction of the costs, both fixed and variable, and the increase of the price increase the profit per unit and this leads to an overall increase in profits. In this condition, shorter breaks are preferable in all possible configurations since they reduce the nonworking time and increase the total production; in fact, the pauses of 20 min are always the best ones. Furthermore, the advantages associated to a greater number of breaks are more evident in the case of breaks by 30 min, which is noted in the net increase of profits in the passage from one to four break pauses. Otherwise, when the costs rise or the price drops, the reduction of the profit per unit greatly lowers the economic performance of the system and it entails the convenience of longer breaks than the previous case. In this situation, the scenarios with four breaks amounting 30 min always represent the best choice, and in general 25 and 30 min of breaks are economically preferable especially with distributions of 3 and 4 breaks. Such variations are caused to the different impact of scrap costs, break costs, and revenues when the economic parameters of the examined case study change.

The analyzed results provide a wide overview of the potentialities of SHERPA simulator in the analysis and evaluation of the work-rest policies, which are influenced by several intrinsic system factors such as environmental and individual factors as well as the economic value of the process carried out by the worker. Despite the best breaks configuration for the system varies as a function of several factors and it cannot always be generalized in advance to different working environments, the case study provides the following results:

- The increase of the total length of the breaks always improves the operator reliability while the economic performance is the result of a trade-off between cost classes with opposed trends. In fact, HR higher values are reflected on the machining quality with lower costs for scrap and reworking, but longer breaks reduce the time worked with an increase of the break costs and a possible decrease in revenues.

- The increase of the number of breaks maintaining fixed the total length has a positive impact on the worker reliability and involves higher profits because the worked hours do not change. This is true especially when the recovery rates are medium or fast, while for the slow rate an excessive fractioning of the rest time limits the reaching of a satisfactory recovery.

Our results cannot be easily compared with the literature due to the presence of several criteria of human performance modelling, as seen previously. However, it is evident that one or more breaks in the shift provide a higher level of human performance, especially with short breaks, as reported in section 3.1. The proposed recovery modelling, based on an HRA approach, is therefore in agreement with the existing literature, even if it analyses this issue from a different point of view. The obtained results highlight the importance of measuring and evaluating both human reliability and work rate in the break scheduling problems, because of their significant economic and qualitative impact on the system performance. As well as the choices of the optimal work-rest policy cannot be separated from economic evaluations in terms of profits, considering the cost of lost production due to break and the quality costs related to operator errors.

The limitations of the current research underscore several issues worthy of additional studies. Many constraints on break scheduling management were relaxed in this first version, given the simulative nature of SHERPA model, as for example the maximal working time without breaks or the minimum and maximum possible break time. Future research should address the integration of these constraints in the simulation model. Furthermore, SHERPA requires additional tests for the validation and the calibration of HRA coefficients, as for example the impact of contextual and individual factors on human performance.

6 Conclusion

Human reliability is a highly relevant factor with a considerable impact on the overall performance of human-intensive working systems. The break scheduling problems emerge in these working contexts where rest periods are indispensable due to features of the tasks to be performed, but despite the impact and the importance of breaks, these are not taken into proper consideration and there are ongoing efforts to develop models for optimal shift scheduling with multiple rest breaks. The SHERPA model efficiently evaluates the impacts of the work-rest policies on the HEP and on the economic system performance. It represents a decision support system for the break scheduling problem that quickly compares different break configurations, changing number, duration, and placement of rest breaks over the work shift, according to whatever sets of constraints imposed by legislation or by internal union agreements for the system under consideration. As evident from the case study, there are many factors that impact the system performance and the results are heavily influenced by the selected work-rest policies. The results obtained have led to the first considerations about the impact of different work-rest policies on the HR levels, but do not reach a univocal economic generalization because of the strong dependence between the value of the process performed by the operator and profit obtained. In any case, SHERPA results represent many different scenarios and discriminate between the different solutions identifying which ones are the more promising. In this perspective, future model developments include the implementation of an automatic algorithm for the selection of the work-rest policies through economic evaluations and widening the spectrum for all possible consequences of human error, such as failures, accidents, delays, compared to the current assumptions. Furthermore, future development of the model, currently underway, address improves to operator recovery modeling.

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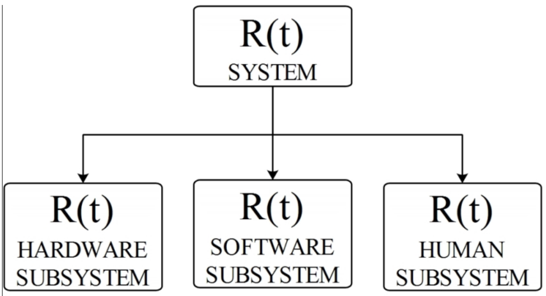


$$R(t)_{SYSTEM} = R(t)_{HARDWARE} \cdot R(t)_{SOFTWARE} \cdot R(t)_{HUMAN}$$

Figure 1: Dimensions of System Reliability (Giuntini, Mathematical characterization of human reliability for multi-task system operations, 2000).

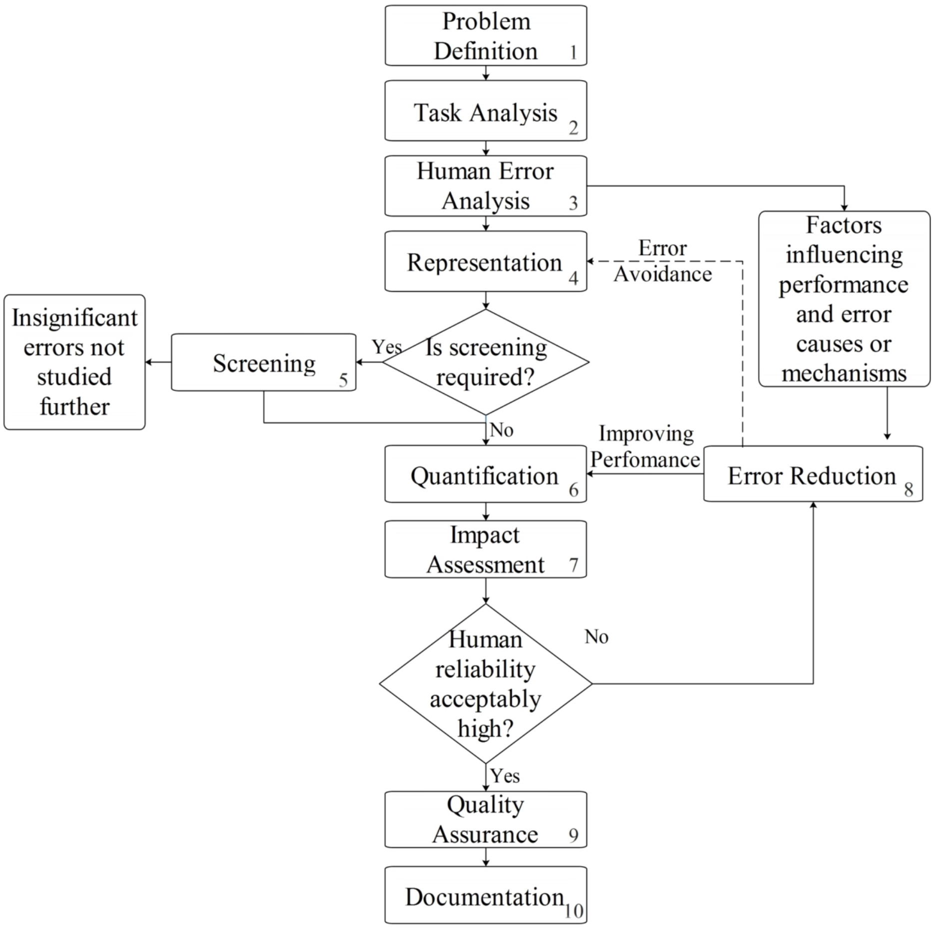


Figure 2: The HRA Process(Kirwan, 1994).

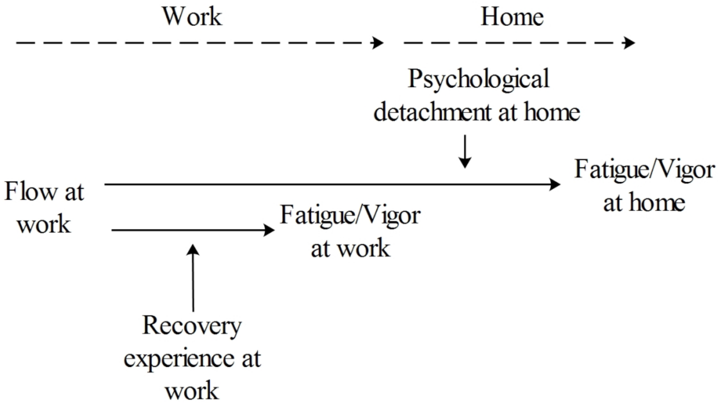


Figure 3: Hypothesized relationships(Demerouti et al., 2012).

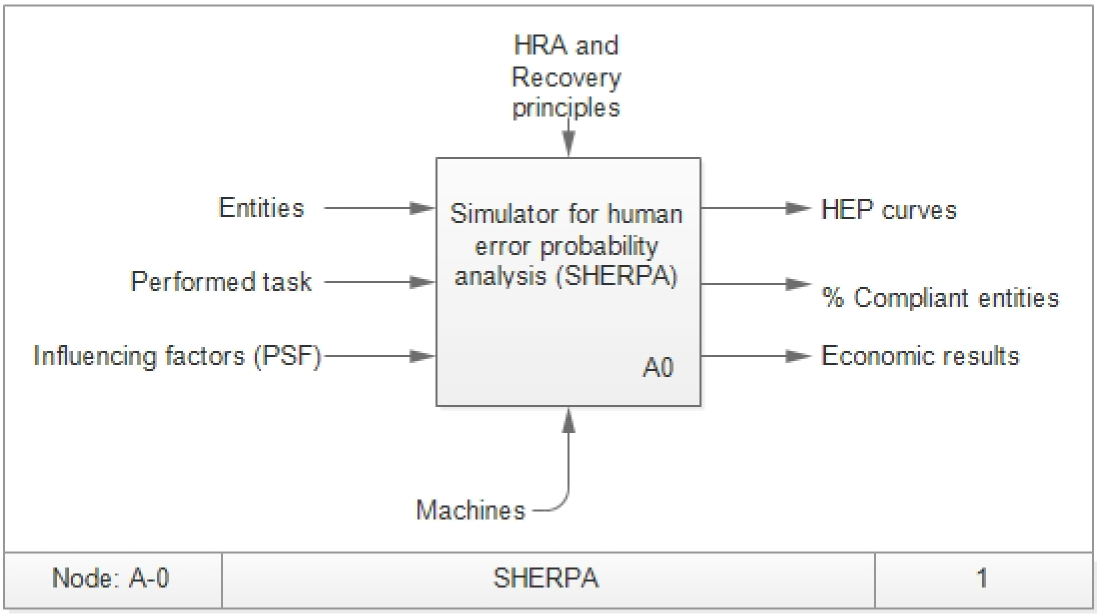


Figure 4: IDEF0 representation of SHERPA simulator.

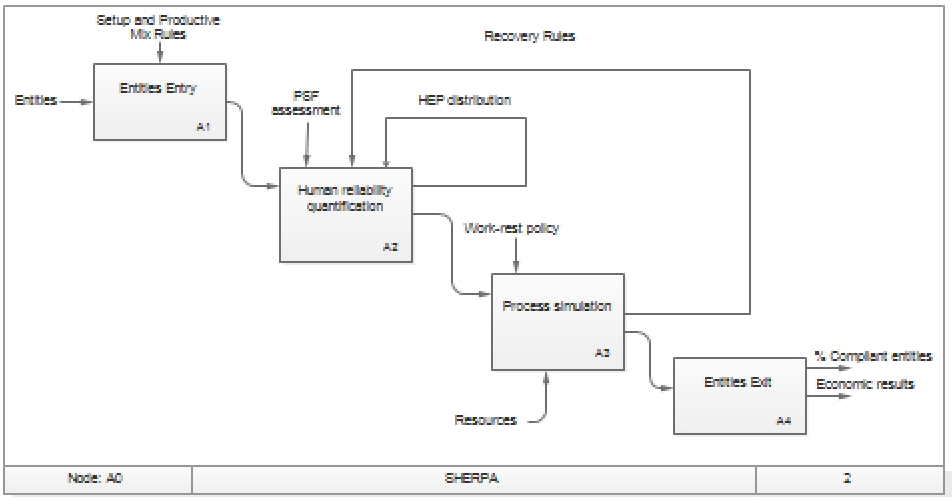


Figure 5: SHERPA decomposition overview.

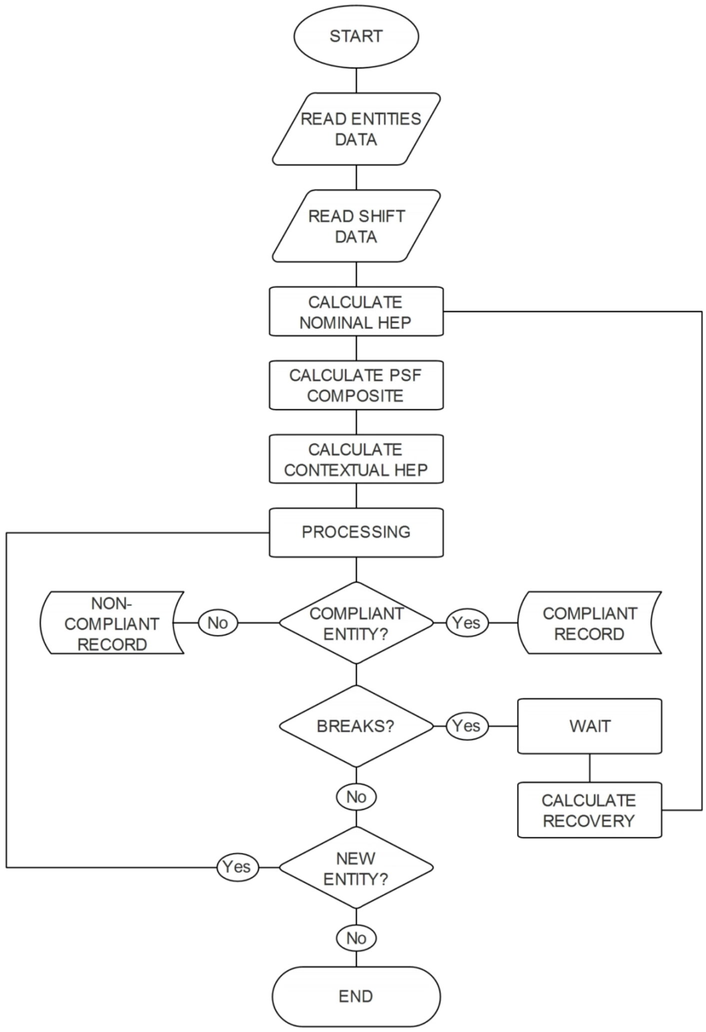


Figure 6: Logical architecture of SHERPA model.

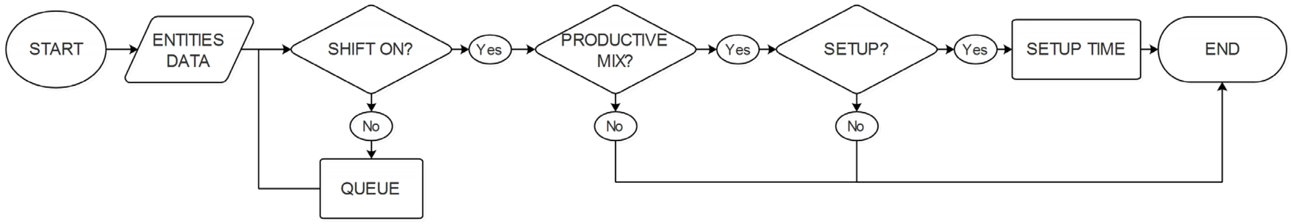


Figure 7: Input logic of the entities with and without productive mix.

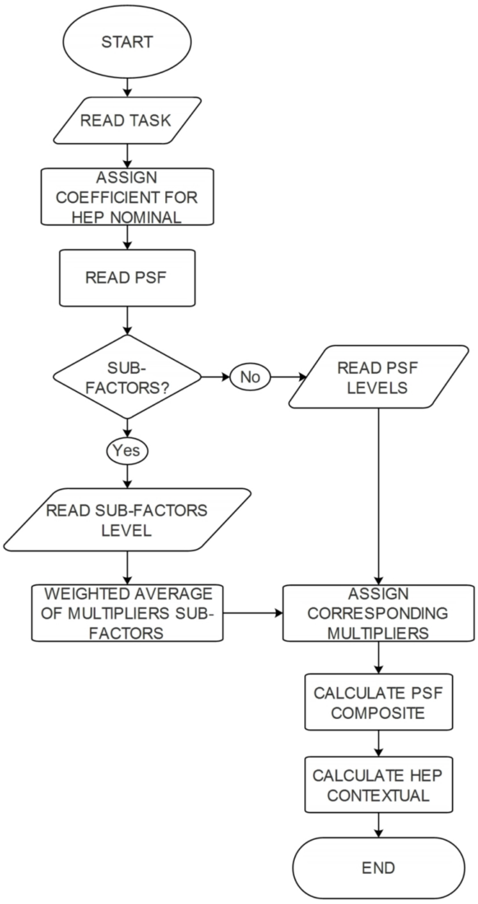


Figure 8: The HRA process in SHERPA model.

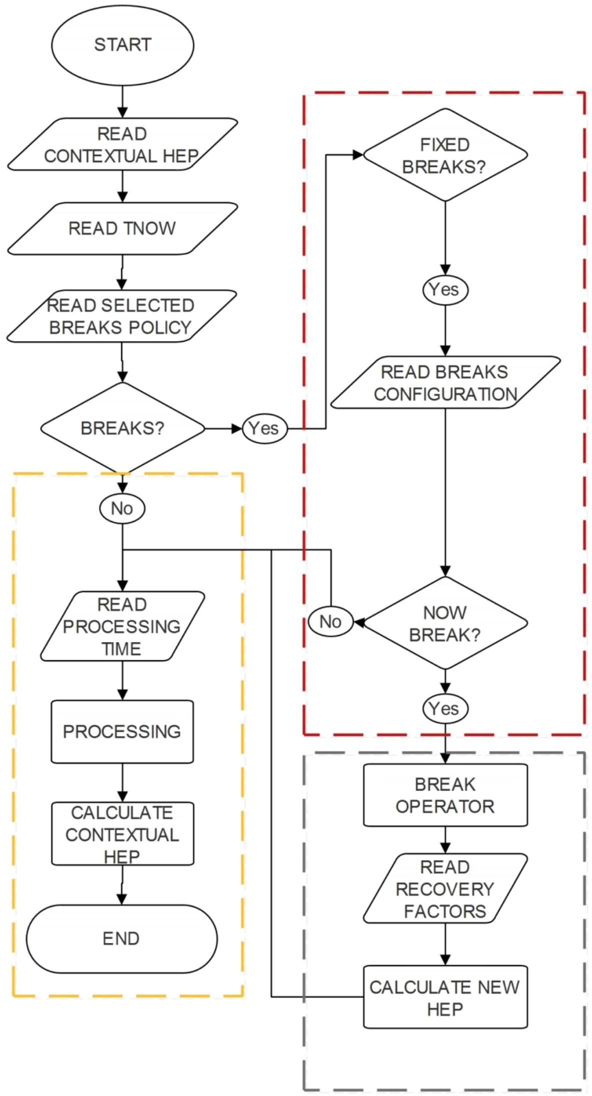
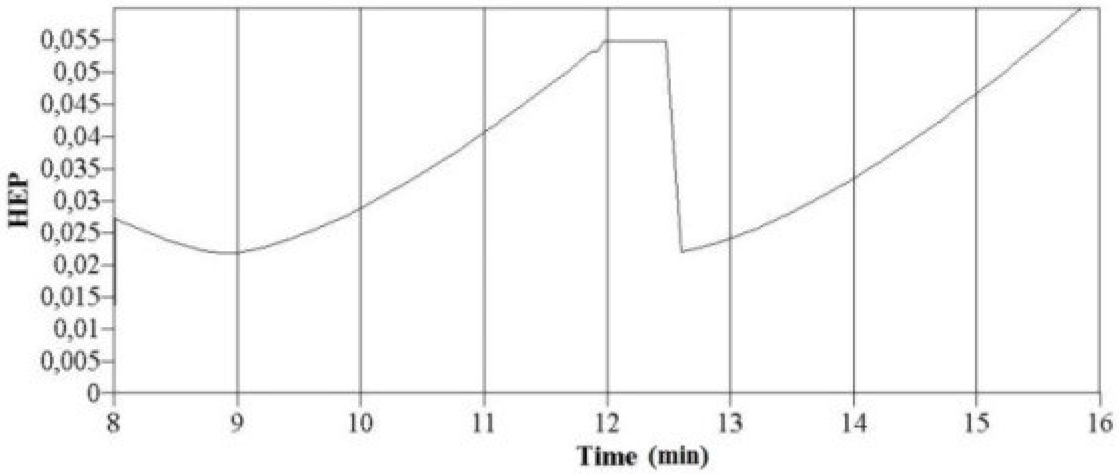


Figure 9: Logic framework of the break configurations management.



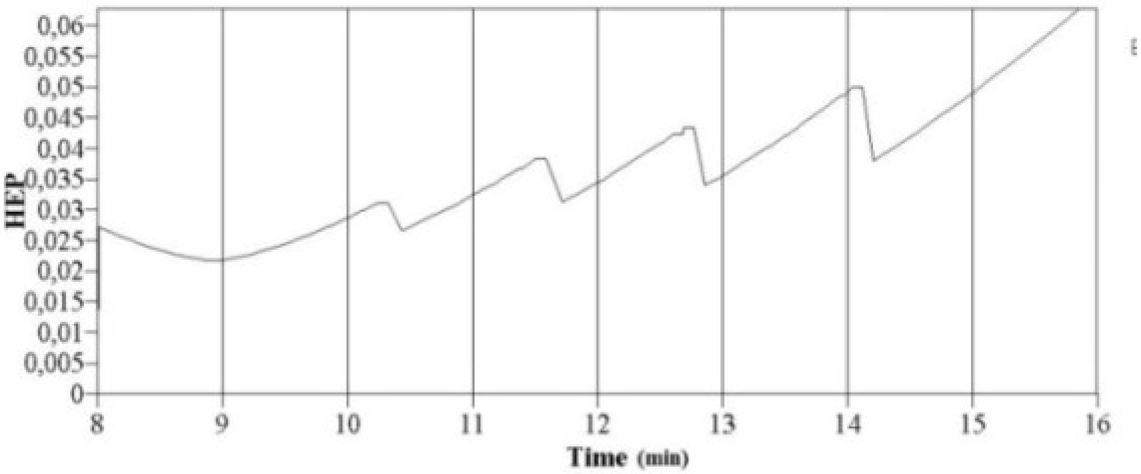


Figure 10: The human error probability distribution with two break configurations: a) one break of 20 min after 240 worked min; b) four breaks of 5 min the first after 132 worked min and the others every 72 min.

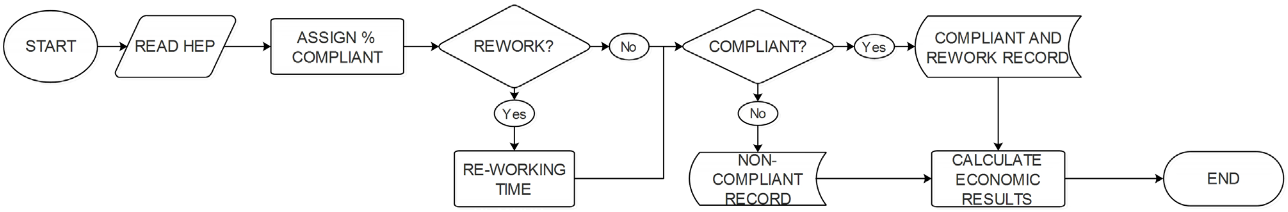


Figure 11: The logic of assignment and quantification of the system outputs.

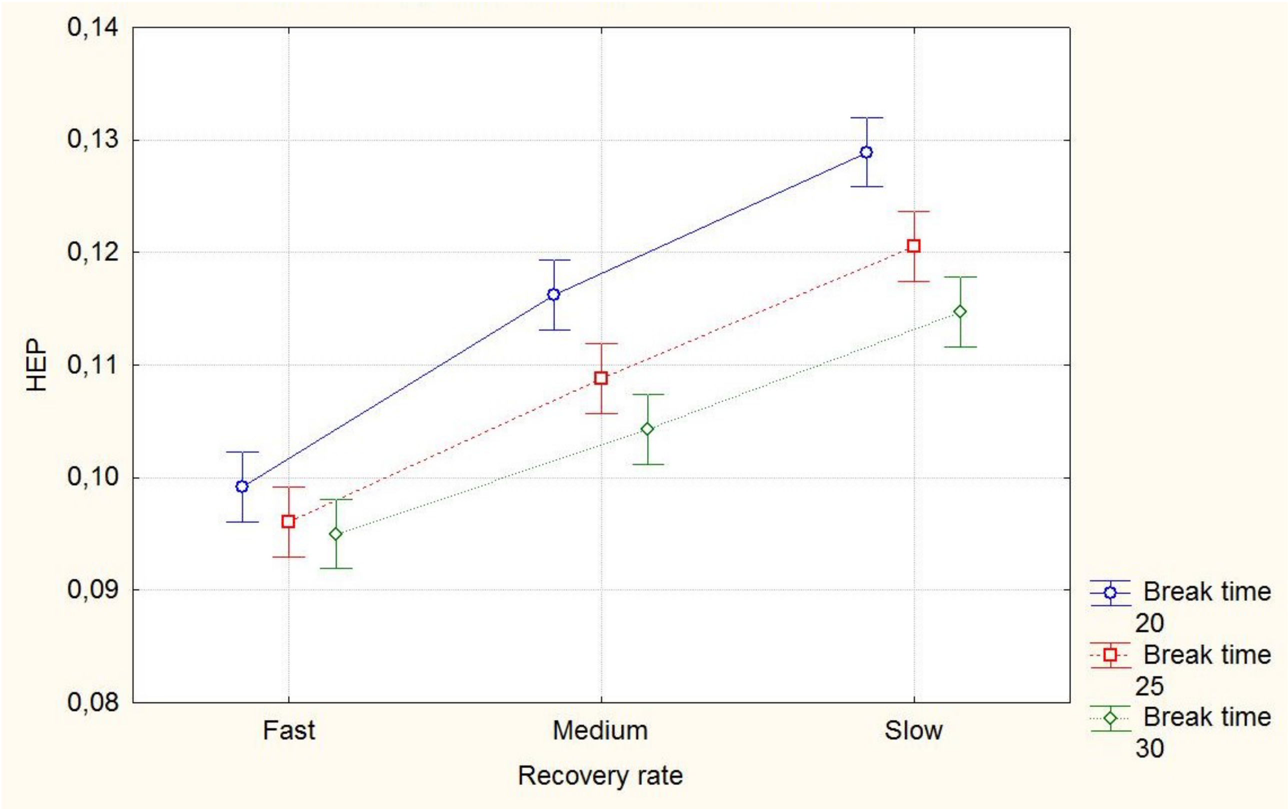


Figure 12: Human error probability value as a function of recovery rate and break total time without distinction of rework class.

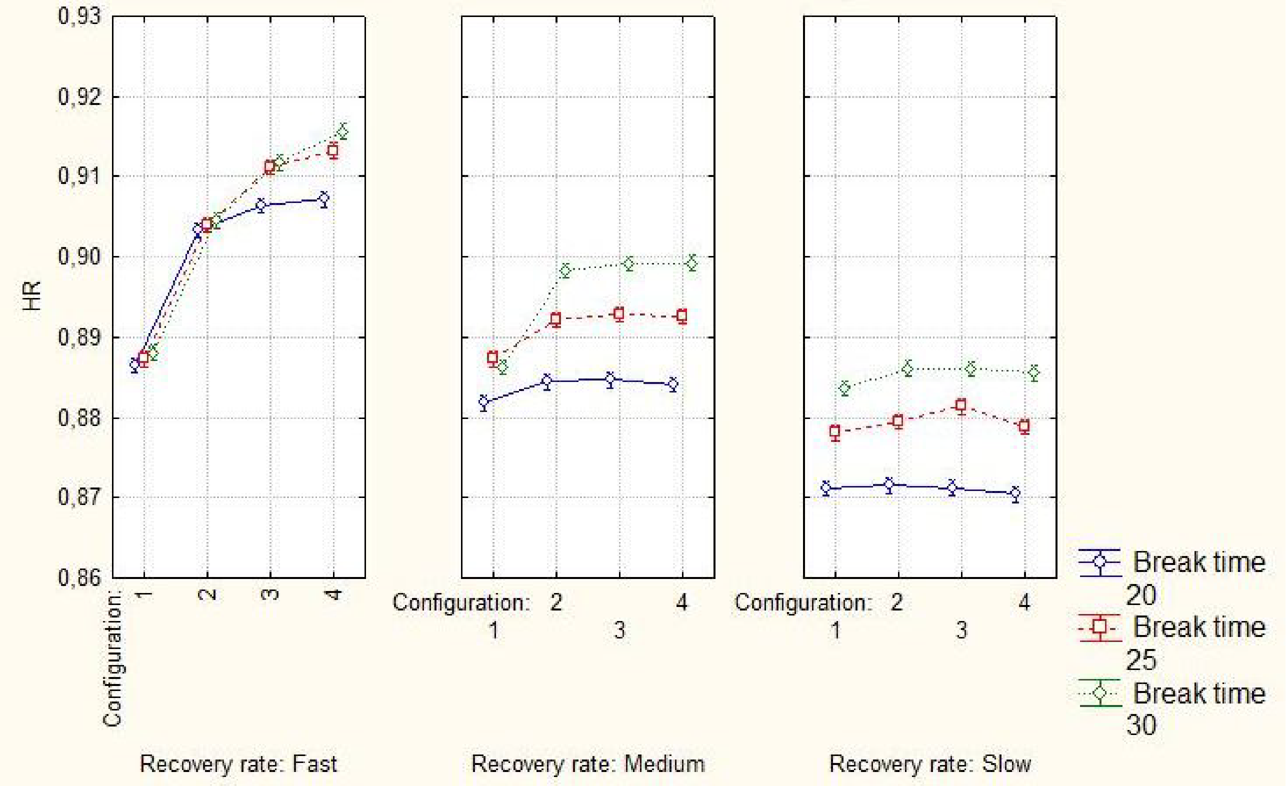


Figure 13: The impact of work–rest configurations in terms of HR.

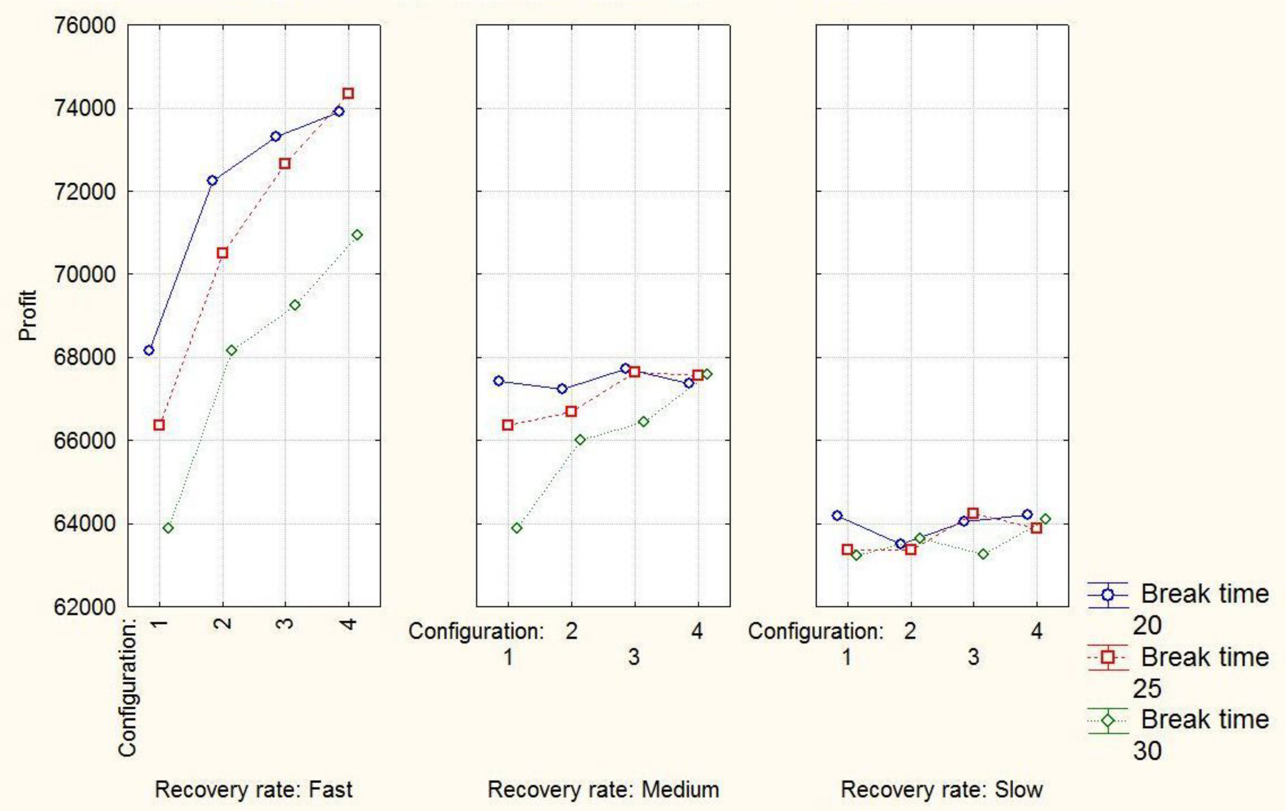


Figure 14: Economic performance (profits in the euro) to changing work–rests policies with fixed rework class (30% reworking probability and 30% reworking time).

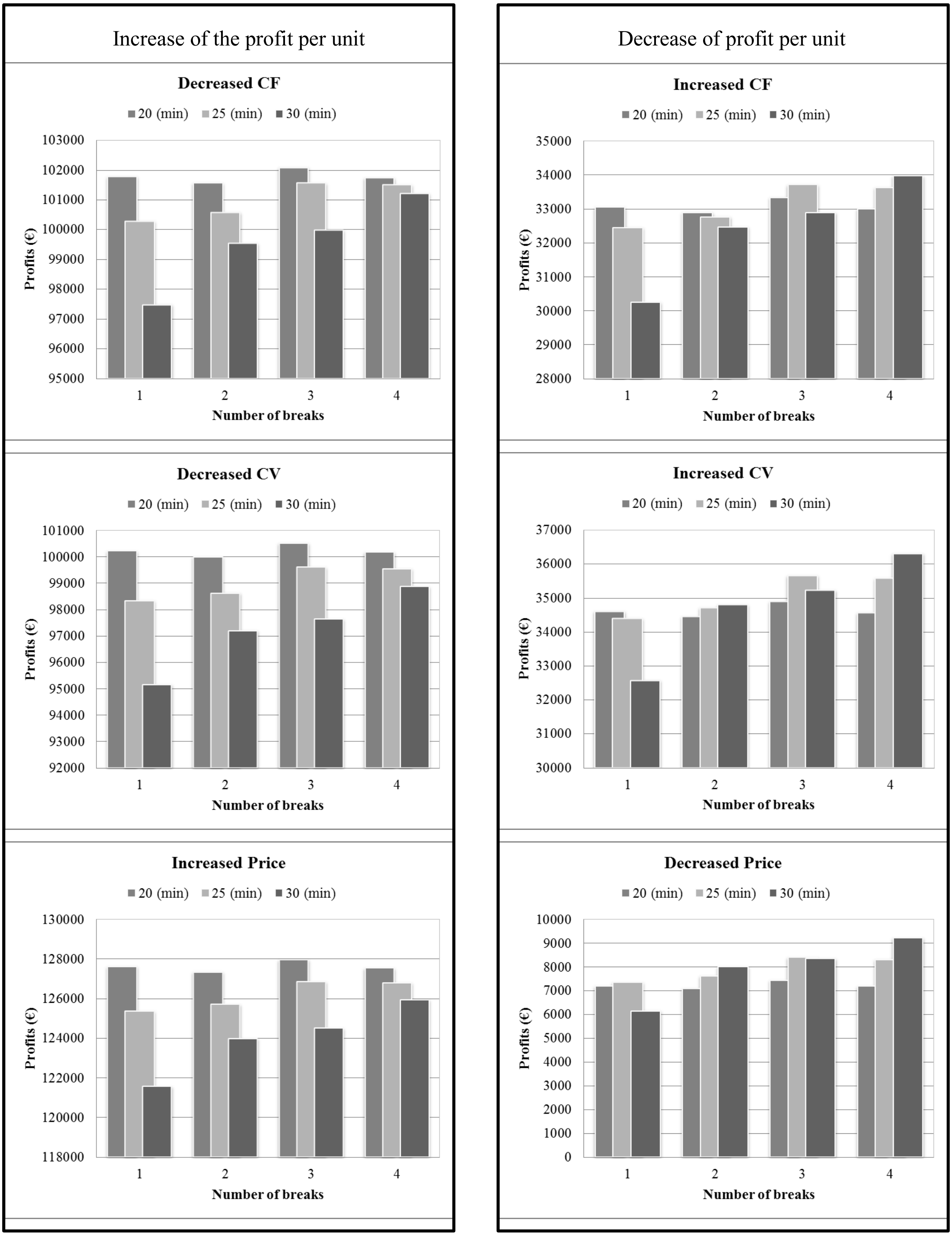


Figure 15: Economic performances with changes in the economic baseline.