An Empirical Approach to Workload and Human Capability Assessment in a Manufacturing Plant

Lorenzo Comberti[1(✉)], Maria Chiara Leva[2], Micaela Demichela[1], Stefano Desideri[3], Gabriele Baldissone[1], and Franco Modaffari[4]

[1] DISAT, Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129 Torino, Italy
lorenzo.comberti@polito.it
[2] School of Food Science and Environmental Health, Dublin Institute of Technology, DIT Kevin Street, Dublin 2 D08 X622, Ireland
[3] IVECO Spa, Suzzara-MN, Italy
[4] CNH Industrial, Via Puglia, 35, 10156 Torino, Italy

Abstract. The Human Factors contribution in the scope of the industrial process optimization presented in this case study had to deal with considerations regarding the physical and mental workload requirements of different workstations and the capabilities of the operators assigned to them. The scope was to provide the industrial management with a better way to allocate human resources to tasks requiring different operational skills. The model developed and customised showed promises results for the case study in which it was applied but offers also a generalizable feature that can extend to other contexts and situations. The assessment performed can contribute to consider necessary areas of improvement in terms of technical measures, procedure optimizations and improved work organization, to reduce defects and waste generation. The paper presents a brief description of the theoretical and empirical approach used to assess the workload of complex tasks in assembly lines and the matching operators' skillsets; furthermore, it also discusses some of the preliminary results of its application.

Keywords: Human Factor · Workload · Human Performance · World class manufacturing

1 Introduction

The main purpose of process optimization in manufacturing is to improve production efficiency and economic benefits. To reach these goals process optimization works through several areas: technical measures upgrading, work organization procedures designing, and, energy saving. There is growing interest in addressing Human Factors as part of these areas [1]. The discipline of Human Factors in fact, has a very relevant role to play, despite the ever-increasing level of automation and the standardization of working-procedures [2]. Quality managers focused their attention to human behaviour

L. Longo and M. C. Leva (Eds.): H-WORKLOAD 2018, CCIS 1012, pp. 180–201, 2019.
https://doi.org/10.1007/978-3-030-14273-5_11

and try to analyse the causes of deviations from procedures where errors are detected [3]. Safety experts included HF into accidents precursor analysis [4, 5] and into ex-post events analysis [6] with the aim of reducing their repetition. HF considerations are used in the area of work organization to reduce operational risks and improve task-time optimization [7]. HF influence has been modelled and measured differently depending on the characteristics of each application. Human Performance modelling is a complex system, where behaviour, cognition, physiology and working condition deeply interact [7, 8]. However the topic of Human reliability analysis and modelling, was initially developed for safety critical industries such as nuclear and aviation and was not widely applied to manufacturing even where humans are still at the forefront of production process that are not completely automated. Automotive for instance is a sector where production systems are based on assembly lines that are required a cross interaction between highly automated workstations and highly trained human resources too. Different operators are needed to contribute towards the final products, which calls for different capabilities for analysing information, recalling items from memory, making decision etc. while performing time constrained tasks. An empirical way to assess human performance, such as the reliability of individuals to perform specific tasks can be a very useful element in the process of allocating human resources to various workstations in an assembly line, as different workstations will present different elements of complexity, ultimately affecting the frequency of defects, human errors [9] and potential unsafe acts [9, 10]. The design of such a system requires an interaction between **task complexity in terms of both mental and physical workload**, and the assessment of the **required human capabilities to cope with it**. The main part of the plant considered as a case study is organised into heavy vehicles assembly lines, which include a sequence of workstations. The level of robotic application is relatively low, most of the tasks are still manually performed As a consequence the impact of human performance on production efficiency is significant; human errors, expressed in term of defects and error of assembly, represent both an increase in cost and waste. The aim of this study was to deliver a Human Performance (HP) modelling capability able to identify areas of improvement in the industrial process so as to produce measurable impact on the rate of human errors. Within the scope of the work was the cooperation with the Management of the manufacturing plant, so as to deliver a practical operational model that could be applied by the plant managers themselves.

Section 2 summarises related work to this paper, while Sect. 3 presents the designing process of the Model. Section 4 shows the model application and Sect. 5 provides an overview of the results and of the future developments for model validation.

2 Related Work

This type of assessment demands a multidisciplinary approach [11] supported by research in the field of Engineering, Psychology and Ergonomics [12]. This work was intended to provide a both a theoretical and an empirical validated approach, and ultimately offer a contribution to the study of human performance optimization in manufacturing. The proposed model is based on previous work presented by the authors where fundamental hypothesis was that Human Performance HP could be represented as directly dependent from two macro-factors [13]:

– Workload (WL): it represents all the factors contributing to the physical and mental demands to execute a given operative task, including work environmental factors [14, 15].
– Human capability (HC): it represents the resources of workers under the real working conditions and includes the physical, mental and cognitive abilities of each worker. As a contribution the authors considered some key hypothesis for the concept of mental workload and how it can be operationalized for practical assessments [16, 17].

3 Design and Methodology

The methodology used to estimate Human Performance in the assembly line can be broken down into five steps (as it is showed in Fig. 1). First step was focused on the "Conceptual Model" designing. This step began with understanding the variables having an influence on Workload and Human Capabilities. Those variables have been initially selected through a literature review balanced by an appraisal of the working conditions of the different workstation and a task analysis [1, 3, 4] of the key activities of the workstations considered for the study in the assembly line. The second step consisted in characterizing the conceptual model to suit the actual empirical situation found in the case study. This process identified, with the support of task analysis method [18], the actual empirical data sources and or proxies to assess the variables of the conceptual model identified from the literature review, so as to be connected with one or more observable and measurable quantities. This process lead to a simplification of the initial conceptual model into a version applicable to the data availability and the needs expressed for the case study. Data-Field collection was dedicated to empirical measurements of all quantities defined in the operative model structure: results were used for Human Performance Assessment involving the assessment of the workload element together with operator's capabilities. The results obtained from the Data-Field collection campaign lead to the Human Performance (HP) assessment, and that is used to plan interventions on the human resources management of the assembly line. A validation period during which results, expressed in term of production efficiency, will be monitored would allow a validation of the proposed model.

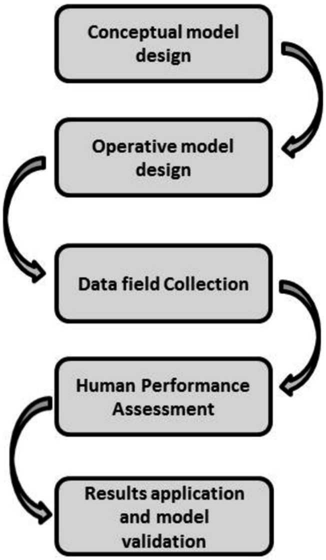

Fig. 1. Project development

3.1 Conceptual Model

The conceptual model is based on the Model developed by Rash [19] In the Rasch model, the probability of a specified outcome (e.g. right/wrong results) is a logistic function of the difference between the person and item difficulty parameter. Let X_{ni} be a dichotomous random variable with binary values where, for example, $X_{ni} = 1$ denotes a correct response and an $X_{ni} = 0$ an incorrect response to a given assessment item. In the Rasch model for dichotomous data, the probability of the outcome is given by the formula provided in Eq. (1):

$$\Pr(X_{ni} = 1) = e^{\beta_n - \delta_i} / 1 + e^{\beta_n - \delta_i} \tag{1}$$

where β_n the ability of person n and δ_i the difficulty of item i.

The model needs to be radically enhanced to take into account an assessment of performance that is not dichotomous and feed into the interaction between two macro factors:

- Human Capability (HC): summarising the skills, training and experience of the people facing the tasks, representing a synthesis of their physical and cognitive abilities to verify whether or not they match the task requirements.
- Workload (WL) summarising the contribution of two main factors [15, 16]: "Mental Workload" (MW) and "Physical Workload" (PW), both associated to each activity identified and analysed in the assembly line.

The reason why we consider mental workload and physical workload together for these type of manufacturing tasks is because recent sensorised EEG experimental studies have shown that the simultaneous executions of tasks, whether physical or cognitive, tends to increase cognitive demands for the human brain [20]. Similarly then, operator capability should be estimated on the basis of the operators' set of cognitive capabilities and physical conditions. The Physical Workload (PW) factor is easily relatable to the physical, motion and postural efforts required to perform a specific task. Poor ergonomic features of the workstation (such as the need to sustain uncomfortable postures and or loads) were related to a remarkable decreasing of performance for discomfort of the worker over time [21], repetitive motions and static task were observed as additional cause for occupational accidents and lower performance [22]. Other factors having an influence on PW are related to the Saturation time: the percentage of the takt-time that is theoretically required to complete the task. The higher the saturation the lower the time available to complete a task. In addition, some general factors able to affect the PW can be summarized into environmental variables [22, 23] which included improper temperature, lighting, noise, vibration and exposure to chemical agents and physical agents as dust. Physiological effects of these environmental factors, under industrial conditions, can contribute to an increase of the stress level and consequently impact the reliability of human performance [24]. Mental Workload is generally related to the amount of mental resources imposed by a specific task [25] but there is no widely accepted definition of it, it can be seen as an interaction between the demands of the task and the performance of the operator [26] or according to Kahneman [27] as: "a factor directly related to the proportion of the mental capacity of an operator spends on task performance". In the literature several methodologies were developed to assess it such as objective physiological measures [28], subjective cognitive analysis [29] and combined multivariate approaches [30]. Generally research in MW assessment have been performed in normative condition, with a simple standardized task and under controlled environmental condition that are not the one faced on the shop floor of the assembly line chosen for this application. However the literature offers more and more empirical studies performed in manufacturing plants [31] related the MW assessment considering ergonomic factors and task complexity on the shop floor and it has also offered recent papers on the effect of task variability over mental workload demands [31, 32]. For the purpose of the empirical study performed MW was assessed on the basis of a combination of subjective measurement and indirect task-related variable quantification, as physiological measurement and cognitive normative test were not approved as a feasible mean of assessment by the industrial partner. As a result of literature review and task analysis performed with plant managers a set of variables relatable to WL were identified. Figure 2 summarizes all variables selected to model WL for the case study.

MW has been assessed on the basis of the following variables (see Fig. 2):

- Task variability: this variable takes into account the effects of parts and product variability and consequently the need to identify and evaluate the appropriate procedural variations for each workstation in the assembly line.
- Task complexity: it represents the effects of remembering how to perform the task.
- Each task is composed by a sequence of simple operations. The higher the number of operations composing the task the bigger is the mental effort required to remember them.

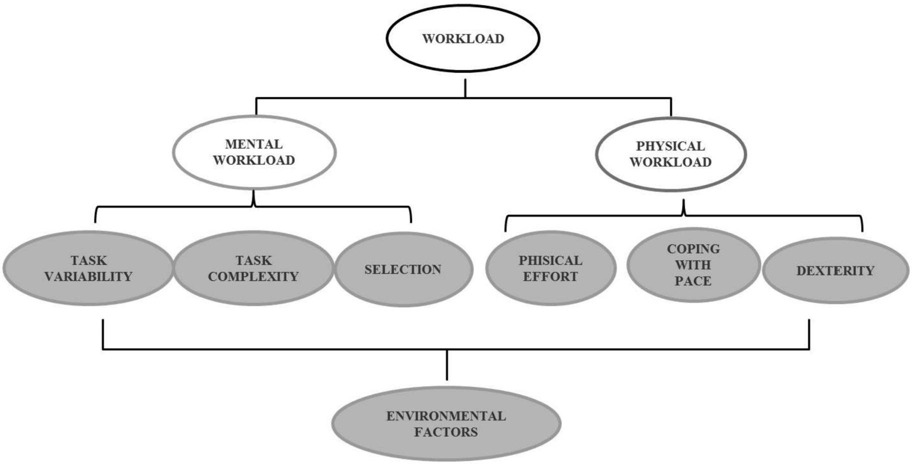

Fig. 2. WL conceptual model

– Selection: some tasks may require a certain degree of decision-making in choosing the right approach during performance that contributes to affect mental workload demand.

PW has been assessed on the basis of the following variables:

– Physical effort: tasks may differ depending to the physical and postural effort required to perform them.
– Coping with pace: in the assembly line all tasks have to be performed in a fixed short period called "takt time". Tasks may differ depending on the percentage of takt-time allocated to complete the task: The higher the saturation the lower the time available to complete a task.
– Dexterity: this variable is intended to measure the manual precision requested by the task characteristics.

Environmental factors take into account all the variables such as: lighting, humidity, noise and temperature that have an impact both on MW and PW. Human Capability (HC), as mentioned in the previous section, represents the total amount of resources that a worker can offer to execute tasks under given environmental working condition. Several human skills have been considered as solicited by the WL associated to each specific task. Human skills that have been considered to model the HC are:

– Manual skill: skills like precision, manual handling, and coordination are solicited continuously during an assembly task.
– Memory: remembering the sequence of operations and parts to be assembled can differ considerably from task to task.
– Physical: the ability of maintaining a constant performance during the shift and coping with pace.

The conceptual model resulting from the combination of WL and HC model is a Human Performance model and it is represented in Fig. 3.

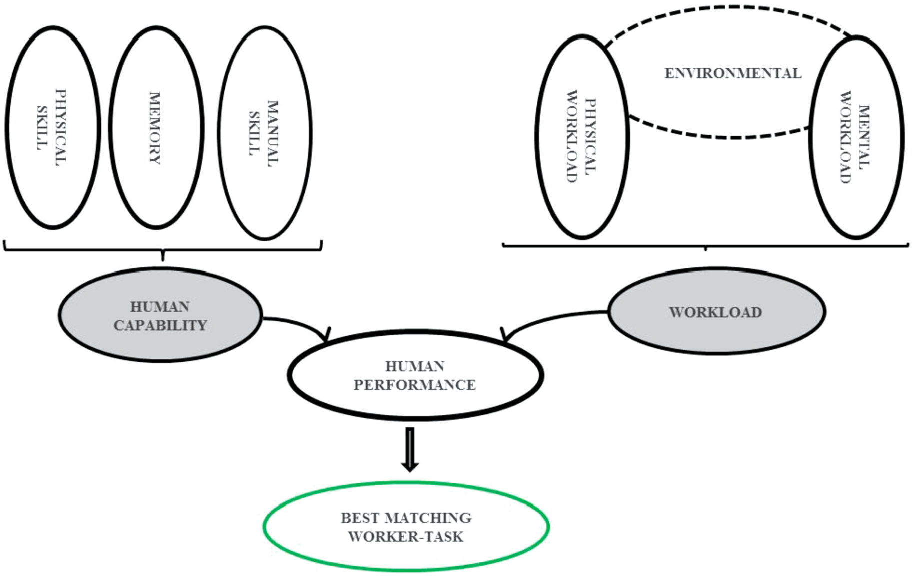

Fig. 3. Human Performance conceptual model

The part of the conceptual model shown in Fig. 3 is to highlight that the variables used to assess WL and HC to assess human performance in relation to each activity analysed for the assembly line. WL is assessed for each activity while the factors chosen to assess Human Capability are specific to each worker. This model provides an estimate of HP index and can be used to identify worker-task matching. This effort is aimed at improving global performance of the assembly line in terms of probability of human error and unsafe acts occurrence.

3.2 Operational Model

The Conceptual model defined in the previous section represented the starting point to define the operative model. To shift from a purely conceptual model to an operational one it was necessary to identify a set of actual observable and measurable quantities to estimate/assess the model variables. In addition to this, a common scale of evaluation for all quantities was adopted so as to allow a quantitative comparison between Human Capabilities (HC) against Workload (WL) requirements. The WL operational model was defined using a task analysis of each workstation activity plus an observation protocol to score the whole assembly line. A participatory approach involved both academic and industry professionals operating in the various management areas: Safety, Work Analysis, Quality, Work-Organization.

Workload Operational Model

Figure 4 shows results of this process with reference to WL operational definition. With reference to Fig. 4 the shift from a conceptual to an operational model implied the exclusion of the "Environmental factors" variable as it was the same for all the workstation and did not appear to have changes and or influence on the overall performance. The environmental conditions were in fact of good quality and therefore did not have an observable impact on performance, furthermore the environmental factors were approximately constant along the production line therefore their effect was not observable in this specific case study. With the exception of the environmental ones all the other variables identified in the conceptual model were matched by one or more observable quantities. Each quantity had a different measurement-unit therefore to adopt a common scale, the indicators were scored according to calibrated Likert scales from 1to 10. Each Likert scale was calibrated according to the original unit measurements of the observable variables.

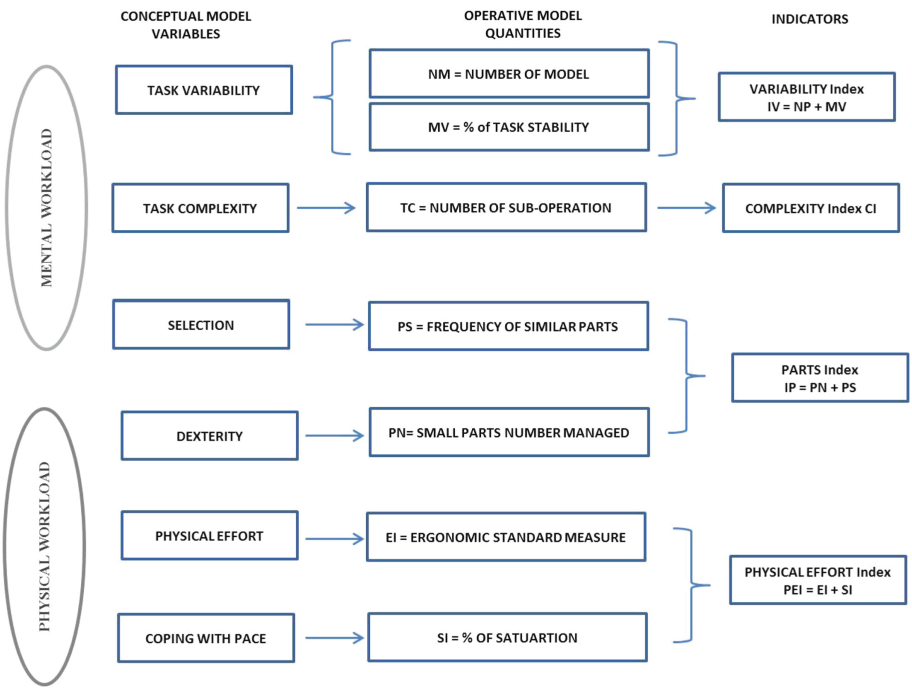

Fig. 4. WL operative model

The choices made to operationalize the conceptual model can be summarised as follow:

– Task Variability was measured considering the following aspect: the assembly line is a sequence of working-places where a shell is moved automatically from a workstation to the next following a certain rate called takt-time. In all working-place a task is performed on the shell according to a specific well defined procedure. Each task is

composed by several operations that can change or remaining constant depending on the kind of product being assembled. To assess this variability two quantities were identified: number of models (NM) represents the number of task variation required by different shell-types in each workstation; NM was assessed between 1 (when the task does not vary following a shell-type variation) and 6 (when there are more than 5 possible task differences following different shell-types). The other factor considered is MV (task stability), which represents the percentage of variations observed in each workstation. MV varied between 0 (when there are no variations depending on the shells being assembled, 100% of tasks in the same type) and 4, when the percentage of the most frequent activities for shell type is only about 60% of the total amount of assembly activities performed during the working day. The combination of this two quantities leads to definition of a numerical index called “Variability index”.
The relation defined to relate these two quantities is expressed by the following equation:

$$IV = NM + MV \tag{2}$$

– Task Complexity refers to the number of basic operations in which the task can be decomposed. This quantity was evaluated with the support of a Work Analyst specialist. Complexity index, “CI”, has a range of variation from 1 (when the basic operations are less than 5) to 10 (when the basic operations are more than 45).
– Selection. This variable was related to the difficulty of making the right choice between similar parts required for assembly on different types of models (as an example 2 kind of screws may differ by 2 mm in length). The Parts Similarity index (PS) was set between a value of “0” (there are no parts similar to each other), and 3, (the percentage of similar parts is more than 30% of the total parts managed during the task). The PS index was combined with Part number index as expressed in Eq. 3.
– Dexterity. This variable was related to the quantity of small parts managed during the task performance. As a consequence a Part number index (PN) was set between 1, (when the small parts managed are less than 5), and 7 (when the parts managed during the task are more than 50). This index has been combined with PS index in Eq. 3:

$$IP = PN + PS \tag{3}$$

IP measures the amount of workload relatable to the quantity and the similarity of small parts to be managed during a specific task, considering the range of PN and PS observable values the index varies between 1 and 10.
– Physical effort and Coping with pace. These variables were related to 2 quantities: the Ergonomic index (EI) and the Saturation index (SI). Both of them are values varying between 1 and 5 depending on the ergonomics assessment of the various workstations (evaluated with a standardized methodology called OCRA [33]) and to the level of saturation of takt-time defined by Work analysis. As a consequence of this the Physical Effort index (PEI) was defined as expressed by Eq. 4:

$$PEI = EI + SI \tag{4}$$

In summary as a consequence of the operational model each workstation would be analysed in term of Physical Workload (PW) and Mental workload (MW) using 4 indicators: IV, CI, IP and PEI.

Human Capability Operational Model

HC represents the total amount of resources that a worker potentially can provide to perform a given task. According to the kind of tasks involved into the assembly line, the HC conceptual model identified 3 set of measurable capabilities: Manual skills, Memory and Physical skill. In order to assess these skills a set of empirical tests were designed. The key conditions considered for the test design process were the followings:

1. The tests have to represents or simulate frequents operations close to the ones performed in the assembly line.
2. The tests have to be performed by workers during the working activity, as a consequence the time requested to perform them needs to be below 10 min.

Considering the above conditions four test were defined:

1. Memory test: sequences of geometric schemes were shown to the worker for few second. The worker was then asked to replicate them on a piece of paper. During this test the time to complete the task and its accuracy were recorded.
2. Precision test: it consists in moving an iron circle along a not linear contour without touching the line. This test is related to the manual precision required in many tasks. During this test the time to complete the path and the number of errors were recorded.
3. Coordination test: In this test the worker is required to use both hands to perform simple actions. Time and precision of coordinate movements were recorded.
4. Methodology test: During this test the worker have to decide and to complete a set of simple assembly steps with small parts. Time and errors were recorded.

Results of these tests have been used to assess the part of the model related to human capability (HC) as reported in Fig. 5.

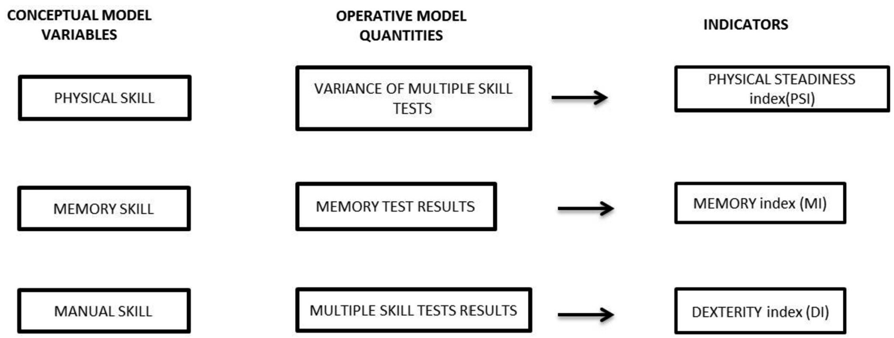

Fig. 5. Human capability operative model

The variables identified in the HC Conceptual model and reported in Fig. 5 are follows:

1. Physical skills: assessed considering the variance in performance on all the tests performed by a single worker. The variance was considered as a proxy of Physical Steadiness. This indicator is express in a scale from 1 to 10, where 10 indicates the capability to attain best consistency in good work performance.
2. Memory skill was associated to the result of the memory test. A memory index was introduced within the 1 to 10 Likert scale.
3. Manual skill was associated to the results of the Precision, Coordination and Methodology tests. All of them represent a measure of dexterity and consequently it was defined as a Dexterity index.

As a consequence of the operational model developed, each worker of the assembly line would be characterized in term of HC with a set of the 3 indicators (PSI, MI, DI) mentioned above.

3.3 Data Field Collection

On the basis of the Operational model and the variable identified it was possible to perform the field data collection campaign. An assembly line of 23 work-stations was selected as test-line. Therefore 23 different WL were calculated according to the indicators reported in Fig. 4. The results of this activity are summarized in Fig. 6. Figure 6 highlights how the WL differs along the assembly line. Workstation 1 for instance has a WL index not far from Workstation 16, while the workstation reporting the highest WL value (with an overall score of 28) is the one marked as number 17.

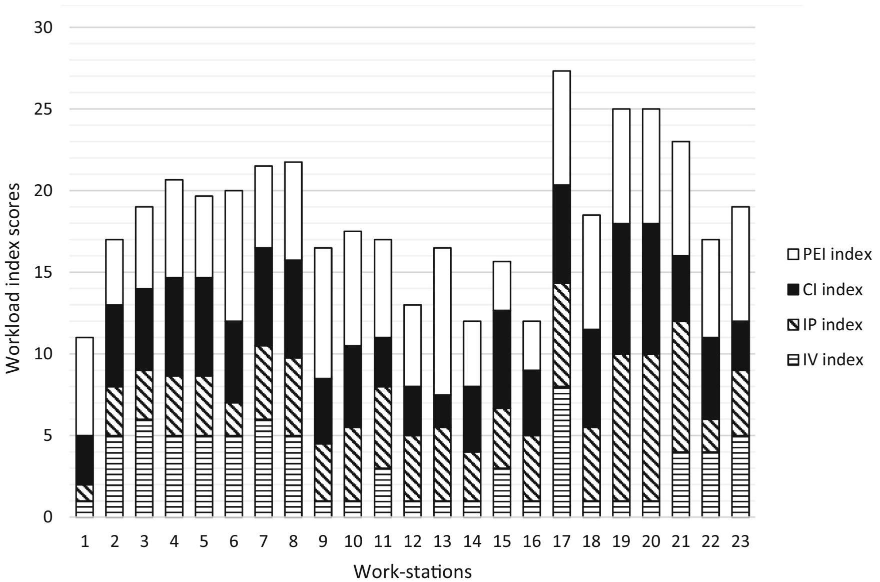

Fig. 6. Work stations workload assessment

The HC assessment campaign with the tests involved directly 50 workers employed in the selected assembly line. The tests were planned so as to minimize the impact on the working activity of the assembly line itself and the average time of execution was between 7–9 min. To perform the tests each worker was given a short break, for the time strictly necessary, and replaced by a substitute. This configuration allowed the tests to be repeated 3 times during the whole shift for all the workers. All test results showed a good discrimination of workers skills highlighting a wide range of variation in performances. The HC indicators were all reported in a numerical scale 1–10 in relation to test results. The test measures 2 quantities: the amount of time spent to complete the test and the number of errors committed during its execution. The two quantities were combined in a single index as reported in Eq. (5). Considering the results of each individual skill test, time and errors observed in the text were linearly combined in a common quantity named "Modified Time" (MT) according to the following equation:

$$MT = \mathrm{Time}[s] + \mathrm{Errors} \times 3[s] \tag{5}$$

Where each error was transformed in an additional amount of time of 3 s. On the basis of the MT distribution the correspondent HC indicator was assessed. Figure 7 shows the results measured in term of Time and number of errors for 25 workers and Fig. 8 highlights the corresponding MT distribution.

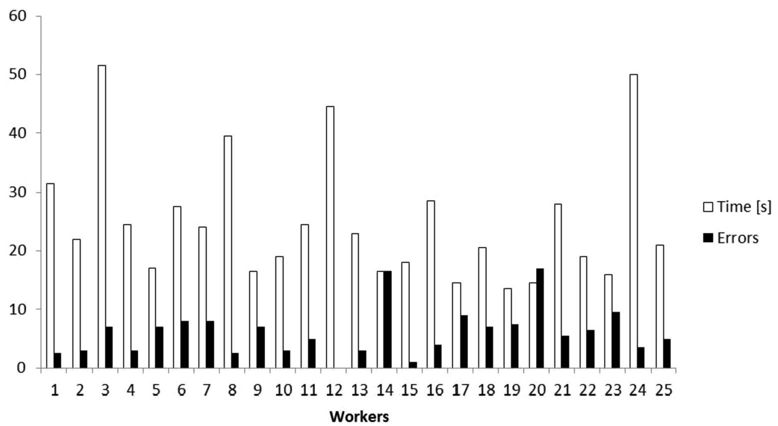

Fig. 7. Precision-test results: time to complete test expressed in second and number of errors

Figure 7 highlights the capacity of the Precision test of discriminating between different skill-levels among workers. The MD assessment (Fig. 8) revealed a wide range of performance variation, from a minimum of 21 s to a maximum of 70 s. On the basis of this range of variation, each MD value was scaled into a numerical index.

This process was repeated for all tests' results, leading to the definition of the required HC indicators for all the workers involved. Figure 9 summarizes the HC distribution.

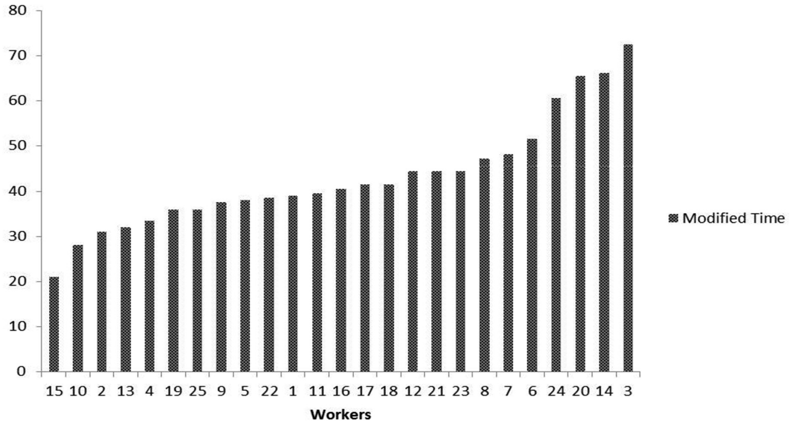

Fig. 8. Modified Time (MT) distribution

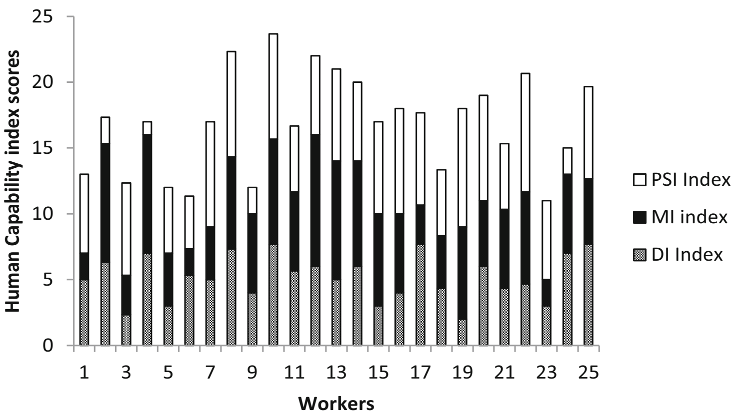

Fig. 9. Human capability index distribution

Figure 9 highlights how HC change even significantly from operator to operator. For each worker it is possible to consider the overall score for HC or the score of each specific skill. For example worker number 6 has the following indicators: PSI = 5, DI = 5 and MI equal to 10 for a total of recorded HC of 20 which is in the highest percentile of the HC values recorded for the overall population. This information suggests that this worker may be better allocated to a workstation where Memory is a key requirement. The effects of HC and WL assessment, with the set of Indicators defined in the Operational model, will be discussed in the next section.

4 Human Performance Assessment

The HP assessment was defined according to the scheme proposed in the Conceptual model (Fig. 3) and in compliance with the operational evaluation process defined for HC and WL. The HP calculation therefore is outlined as follow (see Fig. 10): for each possible matching worker/workstation the combination of the 3 HC index (MI, DI, PSI) with 4 WL index (PEI, IP, CI and IV) lead to an overall matching index reported in Eq. (6):

$$HC_{worker} - WL_{workingplace} = HP \tag{6}$$

The Matching-index assesses the level of adequacy of human capability to the workload determined for each workstation.

Figure 10 outlines an example where the Matching is characterized by:

- Two negatives value due to MI-IV and to DI-PI. These represent a negative matching worker-workstation as the variability (IV) and dexterity required by the task are not well matched by the memory and dexterity scores of the worker.
- Two positive indices representing a favourable matching.

On the basis of the Matching index, two Human Performance assessment indices were defined:

- HPminus: represents the sum of all negatives matching index.
- HPplus: represents the sum of all positive values of matching index.

With these two indexes it is possible to quantify the potential goodness of fit, in term of all the possible matching of workers and workstations.

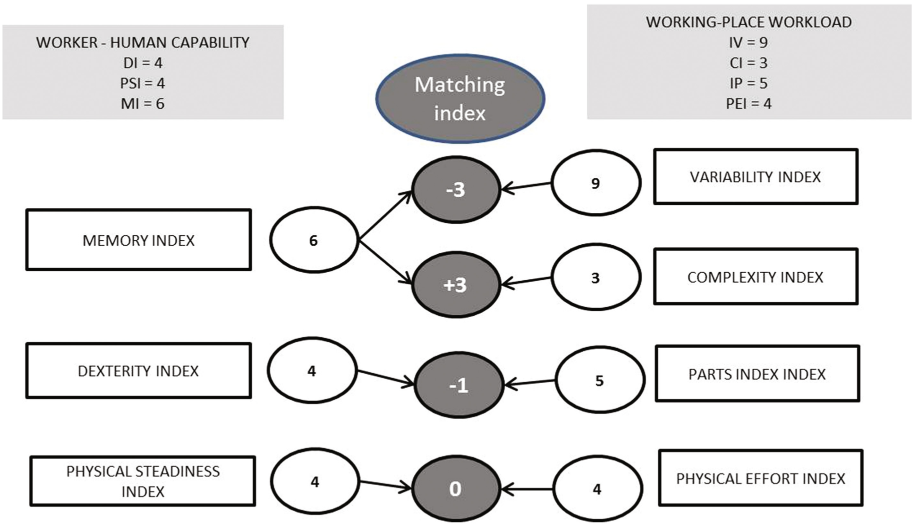

Fig. 10. Human Performance scheme of calculation

This matching index is a predictor of human performance, as the lower the value of HPminus the higher is the probability of human error for that combination. On the basis of this systematic assessment of HPminus and HPplus, for all the possible combination workers/workstation a matrix of matching combination is defined.

Figure 11 summarises the results of this approach showing, as an example the matrix of combinations obtained for 5 workstations and 25 workers (with all their relative HP assessment index). The score of the 25 workers are reported for each workstation in a decreasing order (the workers are in the upper row, and the HP index in the lower row).

1	Workers	AC	AV	AJ	AT	AG	AA	AN	AO	AP	AH	AW	AQ	AE	AF	AI	AU	AA	AD	AK	AL	AM
	HP	23	18	18	13	12	10	8	-1	-1	-2	-2	-3	-3	-3	-3	-3	-5	-5	-6	-7	-7
2	Workers	AC	AV	AJ	AX	AG	AA	AT	AN	AH	AP	AR	AS	AW	AE	AU	AQ	AD	AA	AL	AM	AK
	HP	16	12	11	-1	-2	-3	-3	-3	-4	-5	-5	-6	-7	-8	-9	-9	-11	-11	-11	-11	-13
3	Workers	AC	AV	AJ	AX	AG	AA	AT	AN	AH	AP	AR	AS	AW	AE	AU	AQ	AD	AA	AL	AM	AK
	HP	10	9	9	-1	-2	-3	-3	-3	-4	-5	-5	-6	-7	-8	-9	-9	-11	-11	-11	-11	-13
4	Workers	AV	AJ	AX	AT	AG	AP	AR	AC	AE	AF	AI	AO	AS	AW	AQ	AU	AL	AA	AD	AM	AK
	HP	15	15	8	8	6	5	3	-1	-1	-1	-1	-2	-2	-2	-4	-4	-5	-6	-10	-10	-10
5	Workers	AV	AJ	AX	AT	AG	AR	AC	AH	AO	AS	AW	AF	AI	AE	AU	AQ	AA	AL	AD	AK	AM
	HP	15	14	10	10	9	3	-1	-1	-1	-1	-1	-2	-2	-2	-3	-3	-5	-6	-9	-9	-10

Fig. 11. Matching matrix

A grey-scale was set: black for bad matching (HP assessment index < -4), grey for acceptable matching (HP assessment index between from -4 to -1) and white for good matching. This method in reality is to be used as an optimization problem where the value to be optimized is the HP index. The index needs to be above 0 but as close to 0 as possible to ensure good matching of requirements and capabilities while at the same time avoiding waste. The matrix can be used as guidance tool to support manning activities.

5 Results

The project outlined a proof of concept for a model to evaluate workload requirement and matching operators skills as a predictor of human error in manufacturing tasks. The model was tested in a concrete case study involving an assembly line made of 21 individual workstations and 50 workers divided in two daily shifts named A and B. According to the data field collection scheme reported in Sect. 4, the application of the operational model entailed the WL assessment for the 21 work stations and HC assessment for all workers involved. Figure 12 summarizes the results obtained for the WL assessment.

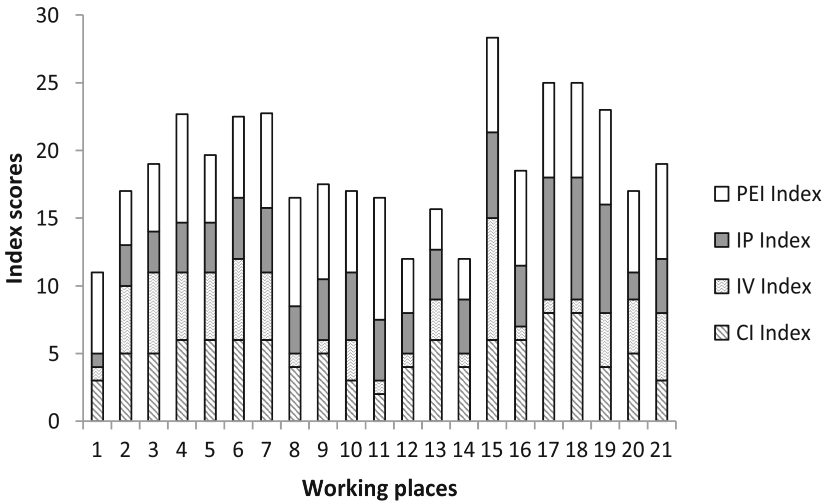

Fig. 12. Workload assessment of the assembly line

Figures 13 and 14 showed the HC values for the workers of the two shifts A and B.

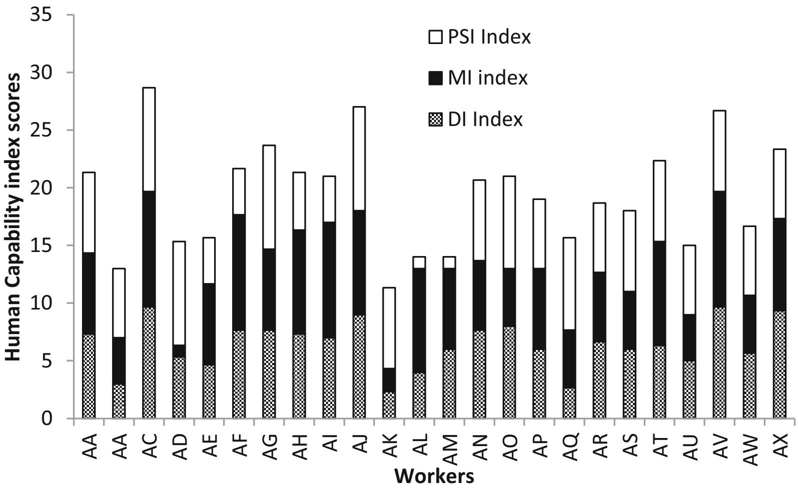

Fig. 13. HC of workers shift A

A Human Performance index was then defined to take into account the evaluation of all the possible matching combinations of workers and workstations. The final result of this activity was presented in two global matching matrixes, one for each shift, with dimensions defined by workstations (number of rows) and workers (number of columns). For our case study the matrix had 21 rows (one for each workstation) and 25 columns (one for each worker). Figure 16 in Appendix summarises the results of this approach showing, as an example, the matrix of combinations obtained for the shift B. On the basis of the matching matrix it would be possible to minimize the negative Human Performance index (HPminus) and consequently to have a better distribution of workers to the workstations. The distribution is determined on the basis of each individual Human Capability and Workload index. The matching-matrixes were used to identify the best configuration of the line in terms of human resources allocation for each shift. According to the plant managers, a period of 1 month has been chosen to monitor the results of the new configuration. The monitoring has been done with 2 observable quality indicators. The first quality indicator was named QI (Quality index) and it measured the percentage of product with no defects produced at the end of the line. This parameter was measured in a quality gate by quality experts according to standardized internal procedures. Figure 15 summarises the QI values collected for a period of 6 months during which the month of May was the one with the configuration workers-workstations defined on the basis of the matching matrix.

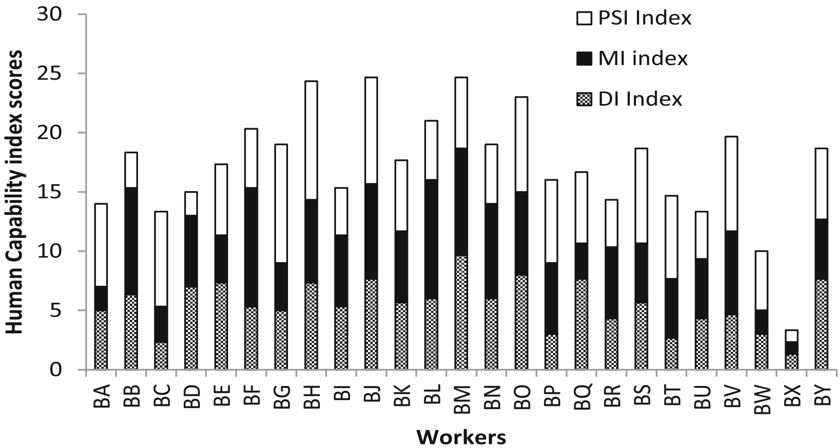

Fig. 14. HC of workers shift B

After this month, due to internal organisational changes a relevant turnover of workers significantly impacted the manning of several lines and it wasn't possible to maintain the observable optimized configuration any more.

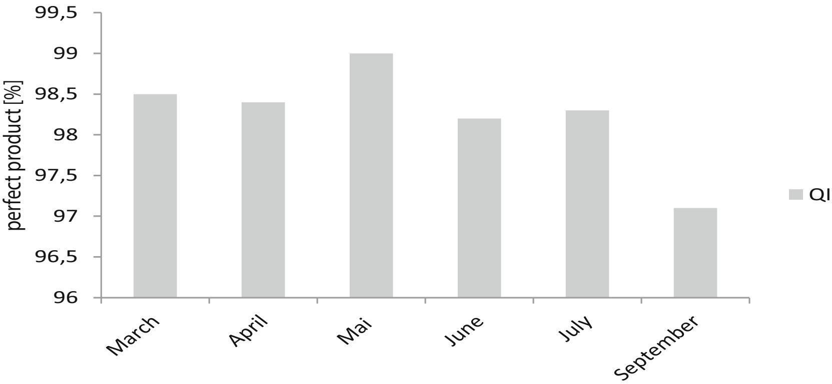

Fig. 15. QI values

The second quality indicator was based on the number of recovery activities performed to solve assembly errors before the quality gate. Supervisors observed a reduction of the recovery activities for both shifts.

6 Discussion

Currently the management of human resources on the production line is decided by the line supervisor, on the basis of his own judgement. The definition of a matching-matrix would means shifting from a total subjective assessment to one empirically and theoretically grounded on evaluation of required workload and available capabilities. The operational model application allowed an empirical quantification of WL and HC, but the model itself is generalizable to other context and configurations. Figure 12 highlights how the WL differs along the assembly line even if all workstations are part of system with a common tack time. In fact, WL varied from a value that goes from 11 (for workstation 1) to 28 (for workstation 15). Not only the total value of WL changes along the line but also the individual factors contributing towards it shows a significant degree of diversification. Some workstations were characterised by a small value of individual variability (IV) index and a relevant value of individual Parts (IP) index (e.g. workstation 16 and 17); while other workstations presented a small value of complexity Index (CI) and IV but a high value of Physical Effort Index (PEI) (e.g. workstation 11). This information shows how the skillset and capability required in term of human resources can significantly change across similar workstations. The assessment of Human Capability (HC) (summarized in Figs. 13 and 14), highlights how HC can significantly vary among workers too. As an example Fig. 13 reports the best HC score for an individual named “AC”, who scored a total value of 28, while worker “AK” obtained the lowest HC score of 12; a significant gap is recorded between the two. Worker AK had very low score in the memory (MI) and dexterity (DI) indexes but an high score in Physical steadiness (PSI) and he can be allocated to those working-stations with lower requirement in Dexterity, Memory and higher requirement in

Physical Effort (e.g. working station 1 or 11). The matching matrix (Fig. 16) can be used as an operational tool to identify the best matching worker-workstation and on the basis of this information line supervisor modified the ordinary allocation for the line. This operation involved more than 60% of the workforce. Managers authorised 1 month of trial during which quality indicators have been collected. The comparison of quality data before and after the reconfiguration has been used to provide a preliminary test of the proposed methodology. Results reported in Fig. 15 highlight that the month of trial scored the best QI index reaching a value of 99%. Even the second quality indicator gave positive results; supervisors monitored the number of recovery activities and found a decrease of their frequency. Unfortunately they did not share a numerical reporting of these activities and this observation remains qualitative. Positive remarks in term of Quality indicators are correlated to human errors reduction during the assembly process and this imply that the HP optimization based on the proposed model can be improved. In addition the introduction of this reconfiguration on the daily working routine was positive perceived and workers generally contributed the rearrangements. On the basis of these preliminary results, plant managers approved an expansion of the project to demonstrate generalisation to more lines over a longer period of time.

7 Conclusion and Future Work

This project was developed to give an effective contribution towards addressing Human performance assessment for manufacturing tasks. The main scope of this work was to develop a model to estimate Human Performance for an assembly process and propose a model to leverage this information to optimize human resources allocation and workstation assessment. This work was carried out using a theoretical approach that was then operationalized to allow empirical data collection. This allowed the theoretical Workload and Human capability assessment to be customised for the real working condition under analysis. A preliminary test line, of 21 working station, was selected as case study and 50 workers have been involved into the testing phase. On the basis of the HP evaluation process a matrix workstations workers allocation was used. The quality indicators collected and the comparison of quality data pre and post reconfiguration has been used to assess the validity of the proposed methodology. On the basis of the preliminary results, plant Managers authorised an expansion of this action research to more production lines in collaboration with the Quality and Production Managers [34]. A set of 5 lines for 100 working stations has now been proposed considering different issues reported by the quality management for recorded human errors. The number of workers to be involved will rise to 340. On the basis of the model results a process of workstations assessment and manning allocation will be defined and a longer period of testing and monitoring will be allowed to discriminate improvements simply due to the so called Hawthorn effect [35]. The results are going to be monitored for a period longer than three months and they will be used to validate and or modify the model, assess its generalization and to verify the possibility to introduce individual motivation among the parameters being considered.

Appendix

Workingplaces		Matching shift B																							
1	Workers	BV	BJ	BC	BX	BT	BG	BA	BN	BO	BP	BR	BS	BW	BQ	BU	BB	BH	BK	BD	BE	BF	BI	BL	BM
	HP	26	25	23	20	20	20	17	16	15	15	14	12	11	10	8	6	-1	-1	-2	-2	-2	-2	-5	-6
2	Workers	BV	BC	BJ	BF	BX	BT	BI	BG	BH	BA	BN	BO	BP	BR	BS	BE	BW	BQ	BB	BU	BL	BK	BD	BM
	HP	20	19	19	15	14	14	14	14	13	11	10	9	9	8	6	6	4.666667	0	-2	-2	-3	-7	-8	-8
3	Workers	BV	BC	BJ	BX	BT	BG	BH	BA	BN	BP	BR	BE	BF	BI	BO	BS	BW	BQ	BB	BU	BL	BK	BD	BM
	HP	18	17	17	12	12	12	11	9	8	7	6	-1	-1	-1	-1	-1	-1	-1	-3	-3	-4	-8	-9	-10
4	Workers	BC	BV	BJ	BX	BT	BG	BA	BN	BP	Fi	BH	BO	BS	BW	BE	BF	BI	BQ	BU	BB	BL	BK	BD	BM
	HP	19	16	15	11	11	10	8	6	5	4	-1	-1	-1	-1	-2	-2	-2	-2	-3	-4	-5	-8	-9	-10
5	Workers	BV	BJ	BC	BX	BT	BG	BH	BA	BN	BP	BR	BE	BF	BI	BO	BS	BW	BQ	BU	BB	BL	BK	BD	BM
	HP	17	16	14	12	12	11	11	9	7	6	5	-1	-1	-1	-1	-1	-1	-2	-3	-4	-4	-8	-9	-9
6	Workers	BV	BJ	BX	BT	BG	BH	BA	BN	BP	BR	BC	BE	BF	BI	BO	BS	BW	BQ	BU	BL	BB	BD	BM	BK
	HP	15	15	10	10	9	9	7	5	5	3	-1	-1	-1	-1	-2	-2	-2	-4	-4	-5	-6	-10	-10	-10
7	Workers	BV	BJ	BX	BT	BG	BA	BN	BP	BR	BC	BH	BO	BS	BW	BF	BI	BE	BU	BQ	BB	BL	BD	BK	BM
	HP	15	14	10	10	9	7	5	4	3	-1	-1	-1	-1	-1	-2	-2	-2	-3	-3	-5	-6	-9	-9	-10
8	Workers	BC	BJ	BG	BO	BQ	BA	BN	BS	BT	BV	BP	BR	BU	BW	BX	BB	BD	BH	BE	BF	BI	BK	BL	BM
	HP	24	20	14	10	-1	-1	-1	-1	-1	-1	-2	-2	-2	-2	-2	-3	-3	-3	-4	-4	-4	-4	-7	-8
9	Workers	BV	BJ	BC	BT	BG	BA	BN	BO	BS	BP	BR	BW	BX	BQ	BH	BU	BE	BF	BI	BB	BD	BK	BL	BM
	HP	19	19	16	14	13	11	9	9	6	-1	-1	-1	-1	-2	-2	-2	-3	-3	-3	-4	-4	-5	-7	-7
10	Workers	BC	BV	BJ	BX	BT	BG	BA	BN	BO	BP	BR	BS	BW	BU	BH	BB	BF	BI	BE	BQ	BD	BK	BL	BM
	HP	21	20	19	14	14	14	11	10	9	9	8	6	5	2	-1	-2	-2	-2	-2	-2	-4	-5	-6	-8
11	Workers	BC	BJ	BG	BD	BO	BA	BN	BS	BT	BV	BQ	BP	BR	BU	BW	BX	BH	BK	BB	BE	BF	BI	BL	BM
	HP	20	20	14	-1	-1	-2	-2	-2	-2	-2	-3	-3	-3	-3	-3	-3	-4	-4	-5	-5	-5	-5	-9	-9
12	Workers	BV	BJ	BC	BF	BX	BT	BI	BG	BH	BA	BN	BO	BP	BR	BS	BE	BW	BU	BB	BQ	BK	BD	BL	BM
	HP	25	24	23	20	19	19	19	19	18	16	15	14	14	13	11	11	10	7	5	0	-3	-3	-3	-4
13	Workers	BV	BJ	BF	BX	BT	BI	BG	BH	BC	BA	BN	BP	BR	BE	BO	BS	BW	BL	BU	BQ	BB	BM	BK	BD
	HP	21	20	16	16	16	15	15	15	14	13	11	10	9	7	-1	-1	-1	-2	-2	-2	-3	-5	-6	-7
14	Workers	BV	BJ	BC	BF	BX	BT	BI	BG	BH	BA	BN	BO	BP	BR	BS	BE	BW	BU	BB	BQ	BL	BD	BM	BK
	HP	25	24	24	20	19	19	19	19	18	16	15	14	14	13	11	11	10	7	-1	-1	-2	-3	-3	-4
15	Workers	BC	BV	BJ	BT	BA	BG	BX	BH	BN	BP	BF	BI	BR	BO	BS	BE	BW	BQ	BL	BU	BB	BD	BK	BM
	HP	11	9	9	4	-1	-1	-1	-2	-2	-2	-3	-3	-3	-4	-4	-6	-6	-8	-8	-8	-10	-13	-14	-14
16	Workers	BC	BV	BJ	BT	BG	BA	BN	BO	BP	BR	BS	BX	BH	BW	BQ	BE	BF	BI	BU	BB	BD	BK	BL	BM
	HP	23	18	18	13	12	10	8	-1	-1	-1	-1	-1	-2	-2	-3	-3	-3	-3	-3	-5	-5	-6	-7	-7
17	Workers	BC	BV	BJ	BX	BG	BA	BT	BN	BH	BO	BF	BI	BP	BR	BS	BW	BE	BU	BQ	BD	BB	BL	BM	BK
	HP	16	12	11	-1	-2	-3	-3	-3	-4	-4	-4	-5	-5	-5	-6	-7	-8	-9	-9	-11	-11	-11	-11	-13
18	Workers	BC	BV	BJ	BX	BG	BA	BT	BN	BH	BO	BF	BI	BP	BR	BS	BW	BE	BU	BQ	BD	BB	BL	BM	BK
	HP	16	12	11	-1	-2	-3	-3	-3	-4	-4	-4	-5	-5	-5	-6	-7	-8	-9	-9	-11	-11	-11	-11	-13
19	Workers	BC	BV	BJ	BO	BG	BN	BA	BX	BT	BS	BR	BH	BP	BF	BW	BI	BU	BQ	BB	BE	BD	BK	BL	BM
	HP	22	14	13	3	0	0	-1	-1	-2	-2	-2	-3	-3	-3	-3	-4	-4	-5	-6	-6	-9	-10	-10	-12
20	Workers	BV	BJ	BC	BX	BT	BG	BA	BN	BO	BP	BR	BS	BW	BQ	BB	BH	BU	BE	BF	BI	BK	BL	BD	BM
	HP	20	19	17	14	14	14	11	10	9	9	7.666667	6	5	4	-1	-1	-1	-2	-2	-2	-5	-5	-7	-9
21	Workers	BC	BV	BJ	BT	BG	BA	BN	BO	BS	BP	BR	BW	BX	BQ	BH	BU	BB	BE	BF	BI	BK	BD	BL	BM
	HP	23	17.66667	17	12	12	9	8	7	4	-1	-1	-1	-1	-1	-2	-2	-3	-3	-3	-3	-6	-6	-6	-11

Fig. 16. Matching matrix for shift B

References

1. Hong, K., Nagaraja, R., Iovenitti, P., Dunn, M.: A socio-technical approach to achieve zero defect manufacturing of complex manual assembly. Hum. Factor Ergon. Manuf. **17**(2), 137–148 (2007). https://doi.org/10.1002/hfm.20068
2. Baines, T.S., Asch, R., Hadfield, L., Mason, J.P., Fletcher, S., Kay, J.M.: Towards a theoretical framework for human performance modelling within manufacturing systems design. Simul. Model. Pract. Theory **13**(6), 451–524 (2005). https://doi.org/10.1016/j.simpat.2005.01.003
3. Miller, D.P., Swain, A.D.: Human error and human reliability. In: Handbook Human Factor, Wiley, New York (1987)
4. Bosca, S., Comberti, L., Baldissone, G., Demichela, M., Murè, S.: Occupational accident precursors management systems. In: Proceedings of the 49th ESReDA Seminar, Brussels (2015)
5. Baldissone, G., Comberti, L., Bosca, S., Murè, S.: The analysis and management of unsafe acts and unsafe conditions. Data collection and analysis. Saf. Sci. (in press). https://doi.org/10.1016/j.ssci.2018.10.006
6. Comberti, L., Baldissone, G., Demichela, M.: A combined approach for the analysis of large occupational accident databases to support accident-prevention decision making. Saf. Sci. **106**, 191–202 (2018). https://doi.org/10.1016/j.ssci.2018.03.014
7. Lin, L., Drury, C.G., Kim, S.W.: Ergonomics and quality in paced assembly lines. Hum. Factors Ergon. Manuf. **11**, 377–382 (2001). https://doi.org/10.1002/hfm.1020
8. Leva, M.C., Ciarrapica Alunni, C., Demichela M., Allemandi, G.: Addressing human performance in automotive industry: identifying main drivers of human reliability. In: Irish Ergonomics Review 2016 Proceedings of the Irish Ergonomics society Annual Conference (2016)
9. Groth, K.M., Mosleh, A.: A data-informed PIF hierarchy for model – based human reliability analysis. Reliab. Eng. Syst. Saf. **108**, 154–174 (2012). https://doi.org/10.1016/j.ress.2012.08.006
10. Comberti L., et al.: Comparison of two methodologies for occupational accidents pre-cursors data collection, In: 25th ESREL (2015), pp. 3237–3244. CRC Press, Zurich (2015)
11. Baine, T.S., Benedettini, O.: Modelling human performance within manufacturing systems design: from a theoretical towards a practical framework. J. Simul. **1**, 121–130 (2007)
12. Eklund, J.: Ergonomics, quality and continuous improvement conceptual and empirical relationships in an industrial context. Ergonomics **40**, 982–1001 (1997). https://doi.org/10.1080/001401397187559
13. Leva, M.C., Comberti, L., Demichela, M., Duane, R.: Human performance modelling in manufacturing: mental workload and task complexity. In: H-Workload 2017: The First International Symposium on Human Mental Workload, Dublin Institute of Technology, Dublin, Ireland, 28–30 June 2017
14. Longo, L., Leva, M.C. (eds.): Human Mental Workload: Models and Applications. First International Symposium, H-WORKLOAD 2017, Dublin Ireland, Revised Selected Papers, vol. 726. Springer, Heidelberg (2017). https://doi.org/10.1007/978-3-319-61061-0
15. Wickens, C.D.: Mental workload: assessment, prediction and consequences. In: Longo, L., Leva, M.C. (eds.) H-WORKLOAD 2017. CCIS, vol. 726, pp. 18–29. Springer, Cham (2017). https://doi.org/10.1007/978-3-319-61061-0_2
16. Mijović, P., Milovanović, M., Ković, V., Gligorijević, I., Mijović, B., Mačužić, I.: Neuroergonomics method for measuring the influence of mental workload modulation on cognitive state of manual assembly worker. In: Longo, L., Leva, M.C. (eds.) H-WORKLOAD 2017. CCIS, vol. 726, pp. 213–224. Springer, Cham (2017). https://doi.org/10.1007/978-3-319-61061-0_14

17. Leva, M.C., Builes, Y.: The benefits of task and cognitive workload support for operators in ground handling. In: Longo, L., Leva, M.C. (eds.) H-WORKLOAD 2017. CCIS, vol. 726, pp. 225–238. Springer, Cham (2017). https://doi.org/10.1007/978-3-319-61061-0_15
18. Stanton, N.A.: Hierarchical task analysis: developments, applications and extensions. Appl. Ergon. **37**, 55–79 (2004). https://doi.org/10.1016/j.apergo.2005.06.003
19. Rasch, G.: Probabilistic model for some intelligence and attainment tests. University of Chicago Press, Chicago (1980)
20. Mijović, P., et al.: Communicating the user state: introducing cognition-aware computing in industrial settings. Safety Science in press available on line 5th of Janaury (2018). https://doi.org/10.1016/j.ssci.2017.12.024
21. Erdinç, O., Yeow, P.H.: Proving external validity of ergonomics and quality relationship through review of real-world case studies. Int. J. Prod. Res. **49**, 949–962 (2011). https://doi.org/10.1080/00207540903555502
22. Punnett, L., Fine, L.J., Keyserling, W.M., Herrin, G.D., Chaffin, D.B.: Shoulder disorders and postural stress in automobile assembly work. Scand. J. Work Environ. Health **26**, 283–291 (2001)
23. Jung, H.S., Jung, H.-S.: Establishment of overall workload assessment technique for various tasks and workplaces. Int. J. Ind. Ergon. **28**, 341–353 (2001). https://doi.org/10.1016/S0169-8141(01)00040-3
24. Grandejan, E.: Fitting the Task to the Man – An Ergonomic Approach. Taylor and Francis, London (1985)
25. Wickens, C.: Multiple resources and mental workload. Hum. Factors **50**(3), 449–455 (2008)
26. Cain, B.: A review of mental workload literature. Report No. RTO-TR-HFM-121-Part-II, Defense Research and Development Canada Toronto Human System Integration Section (2007)
27. Kahneman, D., Tversky, A.: Prospect theory: an analysis of decision under risk. Econometrica **47**, 263–291 (1979). https://doi.org/10.1142/9789814417358_0006
28. Kramer, A.F.: Physiological metrics of mental workload: a review of recent progress. In: Damos, D.L. (ed.) Multiple Task Performance, pp. 279–328. Taylor & Francis, London (1991). ISBN 0-85066-757-7
29. Di Domenico, A., Nussbaum, M.A.: Interactive effects of physical and mental workload on subjective workload assessment. Int. J. Ind. Ergon. **28**, 977–983 (2008). https://doi.org/10.1016/j.ergon.2008.01.012
30. Miyake, S.: Multivariate workload evaluation combining physiological and subjective measures. Int. J. Psychophysiol. **40**, 233–238 (2001). https://doi.org/10.1016/S0167-8760(00)00191-4
31. Falck, A.C., Örtengren, R., Rosenqvist, M.: Assembly failures and action cost in relation to complexity level and assembly ergonomics in manual assembly (Part 2). Int. J. Ind. Ergon. **44**, 455–460 (2014). https://doi.org/10.1016/j.ergon.2014.02.001
32. Lelis-Torres, N., Ugrinowitsch, H., Apolinário-Souza, T., Benda, R., Lage, G.M.: Task engagement and mental workload involved in variation and repetition of a motor skill. Sci. Rep. **7**(1), 14764 (2017). https://doi.org/10.1038/s41598-017-15343-3
33. Colombini, D., Occhipinti, E., Alvarez-Casado, E: The revised OCRA checklist method. Humans factor editorial, Barcelona. (2013). ISBN 978-84-616-2965-7
34. Greenwood, D.J., Levin, M.: Introduction to Action Research: Social Research for Social Change, 2nd edn. Sage Publications, London (2007). ISBN 1-4129-2597-5
35. McCarney, R., Warner, J., Iliffe, S., Van Haselen, R., Griffin, M., Fisher, P.: The hawthorne effect: a randomised, controlled trial. BMC Med. Res. Methodol. **7**, 30 (2007). https://doi.org/10.1186/1471-2288-7-30