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A multimeasure-based methodology for the ergonomic effective design of manufacturing system workstations

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ABSTRACT

The paper proposes a multimeasure-based methodology that can be used by production engineers for the ergonomic effective design of workstations within industrial environments. In particular the authors achieve the effective ergonomic design of the workstations belonging to a real industrial plant by using an approach based on multiple design parameters, Design of Experiments (DOE) and multiple performance measures. The industrial plant being considered is made up by 8 different workstations, 14 workers and it manufactures high-pressure hydraulic hoses. The design methodology aims at considering both the interaction of the operators with their working environment and the work methods. To this end, the workstations' actual configurations are compared with several alternative scenarios by using a well-planned experimental design. As support tool for applying the design methodology the authors use Modeling & Simulation (M&S) and a virtual three-dimensional environment for recreating, with satisfactory accuracy, the evolution over the time of the real industrial plant.

Relevance to industry: The authors propose a methodology for the effective ergonomic design of workstations within industrial plants. The methodology based on multiple design parameters and multiple performance measures supports the design and the evaluation of workstations in terms of both ergonomics and work methods.

1. Introduction

The high complexity of the industrial plants (i.e. manufacturing systems) in terms of interactions between humans and their industrial working environment continuously provides challenging problems for researchers working in this specific field. In effect, during the last years, ergonomic problems became more and more important due to their effects on industrial plants efficiency and productivity. A number of different research works and scientific approaches have been proposed, trying to achieve the ergonomic effective design of the workstations belonging to industrial plants.

In the late 90s, the ergonomic effective design of manufacturing system workstations was mostly supported by videotaping systems used for data collection, i.e. the videotape of the worker performing the manufacturing operations is used for collecting informations about the work methods (Das and Sengupta, 1996; Kadefors and Forsman, 2000; Scott and Lambe, 1996). In order to achieve the ergonomic effective design of the manufacturing system workstations, such research works analyze the videotape of the work methods and assume a trial and error methodology (in effect the design methodology is never supported by a well-defined experimental design). The final ergonomic design of the workstations depends on researcher's experience and his/her knowledge about the manufacturing system. In addition, the design methodology is usually based on a single ergonomic performance measure (i.e. lift index, energy expenditure measure, work postures, etc.) related to a specific ergonomic standard such as the Ovako Working Posture analysis System (OWAS), the Burandt–Schultetus analysis, the NIOSH 81 and NIOSH 91 equations (NIOSH stands for National Institute for Occupational Safety and Health), the Garg analysis. Examples of research works that propose a design methodology for manufacturing system workstations based on a single ergonomic performance measure are Kharu et al. (1981), Engels et al. (1994), Temple and Adams (2000), Lin and Chan (2007), Waters et al. (2007). The integration of two or more ergonomic standards (design methodology based on multiple performance measures) was the successive step carried out by the researchers working in this specific area for achieving multiple and simultaneous ergonomic improvements. Examples of ergonomic standards integration can be found in Wright and Haslam (1999) and Russell et al. (2007).

Another important issue to take into consideration in the manufacturing workstations design is the relation between the concepts of work measurement and ergonomics. The measurement

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of the work aims at evaluating the time standard for performing a particular operation. On the contrary, the concept of ergonomics is often indicated as study of work (Zandin, 2001) and studies the principles that rule the interaction between humans and their working environments. In effect the work measurement and the ergonomics affect each other: ergonomic interventions affect the time required for performing the operations as well as any change to the work method affects the ergonomics of the workplace. Laring et al. (2002) and Udosen (2006) take into consideration in their research works both ergonomics and work measurement aspects.

Finally the last important aspect is whether the ergonomic effective design is carried out by analyzing directly the real manufacturing workstations or by using computerized models. Usually the analysis of the real workstations is quite expensive (in terms of money and time) because it requires to "disturb" processes and activities of the manufacturing system. According to Banks (1998), in this context simulation is a problem solving methodology for creating an artificial history of the system, analyzing its behaviour, carrying out what-if analysis. Furthermore, simulation can be jointly used with virtual three-dimensional environments. A virtual three-dimensional environment is a powerful tool for observing the workplace evolution over the time, detecting ergonomic problems that, otherwise, would be difficult to detect. Wilson (1997) proposes an overview on attributes and capabilities of virtual environments devoted to support ergonomic design; Longo et al. (2006) use M&S in combination with 3-D virtual environments, ergonomic standards and work measurement for supporting the effective design of an assembly line still not in existence.

The contribution of the paper to the state of the art is twofold: (i) the authors propose a methodology for achieving the ergonomic effective design of workstations within industrial environments and (ii) apply such methodology to the workstations belonging to a real industrial plant that manufactures high-pressure hydraulic hoses. The methodology is based on multiple design parameters, Design of Experiments (DOE) and multiple performance measures. It takes into account both the interaction of the operators with their working environment and the work methods and it is supported by Modeling & Simulation (M&S) and virtual three-dimensional environments for creating a simulation model of the real manufacturing plant. In particular, the simulation model is used for comparing the actual workstations with workstations' alternative configurations by carrying out a well-planned Design of Experiments based on multiple design parameters. The choice of the workstations final configuration is made according to multiple ergonomic and time performance measures.

The paper is organized as follows. The explanation of the design methodology is made contextually to its application within a real industrial environment (a manufacturing system). To this end, Sections 2 and 3 respectively describe the manufacturing system and the implementation of the simulation model of the workstations. Section 4 explains the design methodology: how to define the multiple design parameters and the multiple performance measures and how to use the Design of Experiment (DOE) for testing a comprehensive set of workstations' different configurations. Section 5 presents the application of the design methodology and the achievement of the ergonomic effective design of the workstations. The last section reports the conclusions that summarize the scientific and academic value of the work.

2. The manufacturing system

The industrial plant considered in this research work manufactures high-pressure hydraulic hoses. The manufacturing plant, AlfaTechnology s.r.l., is located in the South of Italy (Calabria) and covers a surface of about 13,000 m^2. The plant layout is subdivided into two different manufacturing areas. The first one, the Mechanical area, produces fittings and ring-nuts (and some other components used for hydraulic hoses assembly). The second one, the Assembly area, assembles rubber hoses with fittings and ring-nuts in order to obtain the final product.

A preliminary analysis carried out by the company top management shows that the productivity of the Assembly area (evaluated on monthly basis) falls always below the target level causing, as a consequence, delays in Shop Orders (S.Os) completion. The Assembly area consists of 8 different workstations each one performing a specific operation of the hydraulic hoses assembly process. Most of the workstations are characterized by manually performed operations, therefore, the company top management decided to carry out a research study on the ergonomic effective design of the workstations. To this end, the authors propose a design methodology that takes into consideration both ergonomic issues and work measurement. The operations performed in each workstation are described as follows.

1) *Preparation workstation*: according to the S.Os information, the operator takes the main components from the raw materials' warehouse shelves and defines the length of the rubber hose.
2) *Seal Press workstation*: the operator prints on ring-nuts and fittings the quality and traceability identifying numbers by using the Seal Press machine and places the components inside apposite boxes.
3) *Cutting workstation*: the operators take rubber hose rolls from the raw materials' warehouse shelves and cut the rolls according to the S.Os requirements (by using an automated or manual cutting machine).
4) *Skinning workstation*: the operators eliminate a part of rubber at the ends of each hose in order to guarantee a good junction with the fittings.
5) *Assembly workstation*: the operators manually assemble the rubber hoses with fittings and ring-nuts.
6) *Stapling workstation*: the operators tighten the ring-nuts on the hoses by using the stapling machine.
7) *Pressure Test workstation*: the operators test the hydraulic hoses by using a pressure machine (setting a pressure value higher than the nominal value).
8) *Check and packaging workstation*: the operators compare the S.Os requirements and the hoses' characteristics (quality controls), they also put the hydraulic hoses in the shipping cases.

At the end of each operation, the operators set the status "end of the operation" on the company informative system and move the materials to the successive workstation by using a manually operated dolly. Please note that in the remaining part of the paper the term workstation is being used for indicating the place where a specific operation is performed (i.e. assembly workstation, pressure test workstation, etc.) while the term workplace for indicating the entire Assembly area (made up by the workstations before described).

3. The development of the workstations simulation model

The authors believe that a methodology for achieving the effective design of workstations within an industrial environment must take into account all the design parameters affecting the performance measures related to work measurement and ergonomics. However a manufacturing system workstation is a quite complex system characterized by different design parameters (i.e. objects dimensions, tools position, operator work methods). As a consequence, the design methodology should be supported by an approach capable of recreating the complexity of a real manufacturing system workstation. To this end, the authors propose to use Modeling & Simulation supported by a three-dimensional virtual environment. Consequently, the first step of the design methodology application is the development of a simulation model capable of recreating the manufacturing process of the Assembly area. The simulation model development involves three different phases: collect data concerning the Assembly area (data collection phase), reproduce the real system in the virtual environment from both a geometric and work methods point of view (simulation modeling phase) and verify if the simulation model is an accurate representation of the real system (validation phase). Sections 3.1–3.3 get into details of the three phases of the simulation model development.

3.1. Data collection phase

As first step, the authors asked the company top management all the data needed for the simulation model development. Actually only the data regarding the manufacturing system plant layout and the process times of each workstation were available. Therefore the authors spent a two-month period at the Assembly Area collecting data and information about operators' characteristics (age, gender, height, weight and physical condition), dimensions (length, width and height) and weights of all the objects being modelled and analyzing the work methods used by workers for performing the manufacturing operations. Operators' characteristics were used for selecting human models capable of representing as much as possible the real workers. Objects' dimensions and weights were used for designing the geometric models of each workstation. The observation of the work methods was used for reproducing correctly in the virtual environment the manufacturing operations in each workstation.

3.2. Modeling phase

After the Data collection phase, the second step is the implementation of the workstations simulation model. The authors use eM-Workplace by UGS for developing the simulation model (further information on eM-Workplace can be found in the UGS website, http://www.plm.automation.siemens.com/en_us/products/tecnomatix/assembly_planning/process_simulate_human/index.shtml). This phase involves two different steps. The first one concerns the creation of three-dimensional geometric models of the workstations and tools being used during the manufacturing process; the authors indicate such step as *plant layout generation*. The second one regards both human models insertion into the virtual environment and human model training for performing all the manufacturing operations; the authors indicate such step as *human models insertion and training*.

The *plant layout generation* is supported by Pro-Engineer by PTC, an integrated and parametric 3-D Cad software (further information on Pro-Engineer can be found in the PTC website, http://www.ptc.com/products/proengineer/). The authors use Pro-Engineer (Pro-E) for creating geometric models of all the workstations' objects in order to take advantage from its parametric characteristics. In effect this software supports the geometric models modification; such aspect becomes more and more important because the design methodology requires to test workplace different configurations (each workplace or workstation new configuration requires different geometric models). Note that, also eM-Workplace provides the user with an internal CAD, but it is based on Boolean operators and it does not support the geometric model modification (consequently it cannot be used for supporting the design methodology).

Table 1
Data collection for geometric models implementation.

Object Description	Object Type	Weight (kg)	Dimensions (cm) $L \times W \times H$	Workstation
Ring	Component	0.168	Depending on S.O.	All
Fitting	Component	0.336	Depending on S.O.	All
Marking die	Component	1.800	Depending on S.O.	All
Workstation stamp	Component	0.100	Depending on S.O.	All
Scanner	Component	0.400	$12 \times 7 \times 18$	All
Empty bin	Component	0.300	$30 \times 20 \times 15$	All
Rubber hose	Component	1.020	Depending on S.O.	All
Manual operated Dolly	Equipment	35.300	$100 \times 120 \times 76$	All
Rings bin	Equipment	0.300	$30 \times 20 \times 15$	All
Worktable	Equipment	53.200	$120 \times 90 \times 100$	Preparation
Worktable	Equipment	52.700	$150 \times 70 \times 86$	Seal Press
Support table	Equipment	50.120	$106 \times 76 \times 94$	Seal Press
Seal Press machine	Machine	131.250	$65 \times 65 \times 160$	Seal Press
Pallet	Equipment	25.000	$80 \times 120 \times 15$	Seal Press
Cutting automated machine	Machine	310.070	$350 \times 170 \times 220$	Cutting
Cutting manual machine	Machine	240.600	$170 \times 100 \times 150$	Cutting
Worktable	Equipment	51.250	$110 \times 80 \times 75$	Cutting
Skinning machine	Machine	142.500	$70 \times 80 \times 130$	Skinning
Worktable	Equipment	54.050	$150 \times 70 \times 100$	Skinning
Worktable	Equipment	150.620	$440 \times 150 \times 95$	Assembly
Air blower	Tool	8.350	$15 \times 15 \times 20$	Assembly
PC worktable	Equipment	47.540	$90 \times 90 \times 100$	Assembly
Stapling machine	Machine	223.400	$140 \times 80 \times 95$	Stapling
Worktable	Equipment	51.200	$150 \times 70 \times 85$	Stapling
Support table	Equipment	49.100	$100 \times 65 \times 95$	Stapling
Pallet	Equipment	25.000	$80 \times 120 \times 15$	Stapling
Worktable	Equipment	100.800	$240 \times 220 \times 95$	Pressure test
Pressure test and flushing machine	Machine	1020.040	$368 \times 90 \times 150$	Pressure test
Worktable	Equipment	151.600	$400 \times 150 \times 100$	Check and Packaging
Packaging machine	Machine	550.100	$200 \times 135 \times 140$	Check and Packaging

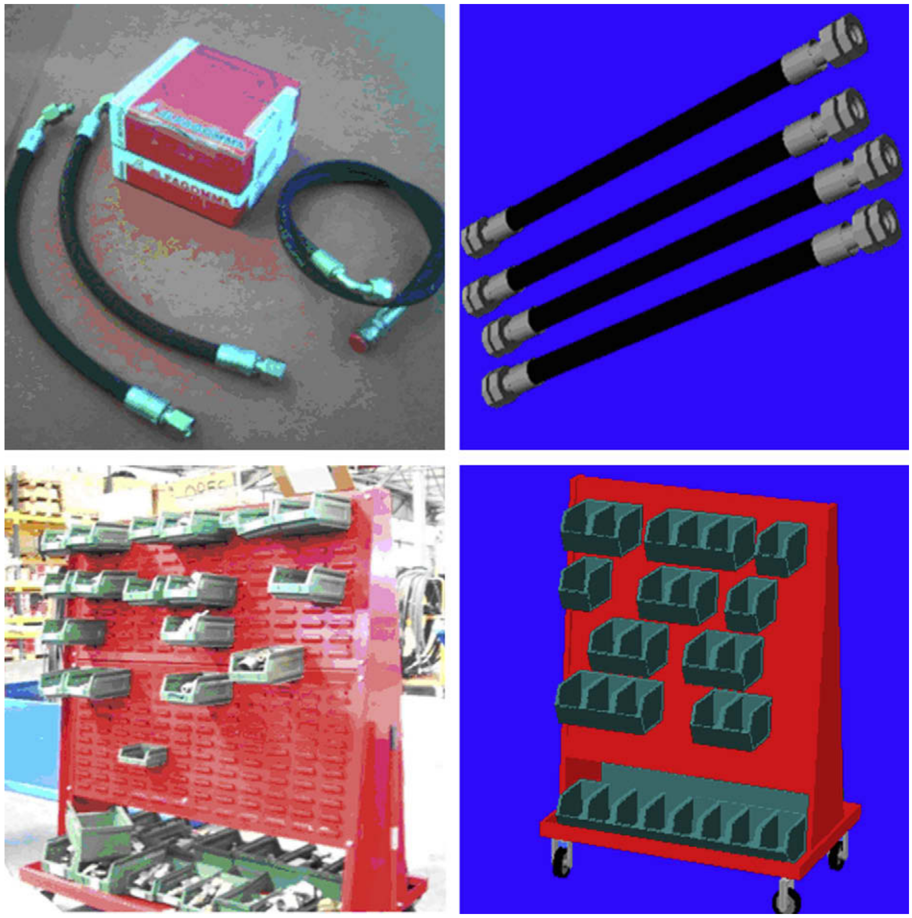

Fig. 1. Real and virtual hydraulic hoses, real and virtual ring bins.

The geometric models generated by using Pro-E contain all the information regarding dimensions, weights and type of materials. For each workstation the geometric models recreate the following elements: machines, equipment and tools, worktables, manual operated dollies, raw materials, containers and cases. Table 1 consists of description, dimensions and weights of the objects being modelled for each workstation.

The Fig. 1 shows the real hydraulic hoses and the real bins used for containing fittings and ring-nuts (left side) and the relative geometric models (right side).

The final step of the *plant layout generation* requires to import the geometric models into the virtual environment provided by the simulation software eM-Workplace. Note that each object has to be positioned in the virtual environment in order to recreate the real plant layout. The Fig. 2 shows the real Assembly and Pressure Test workstations (left side) and the geometric models into the eM-Workplace virtual environment (right side). Finally Fig. 3 shows a panoramic view of the virtual layout of the Assembly area including different workstations.

The second step of the simulation model development is the *human models insertion and training*. The eM-Workplace provides the user with different human models libraries. The selection of the human models takes into account the characteristics of the real operators (age, gender, height, weight and physical condition) with the aim of importing in the virtual environment human models as much as possible similar to the real workers. Table 2 consists of operators' characteristics in terms of age, gender, height, weight and workstation where he/she usually works.

Note that the simulation model must recreate with satisfactory accuracy only the Assembly area as well as the results of the simulation model must be used only for the Assembly area. For this reason the data reported in Table 2 represent only the anthopometry of the workers of the Assembly area (not the whole working population). Obviously each human model needs to be trained in order to perform the manufacturing operations. To this end, eM-Workplace provides the user with a programming language for teaching the basic motions of each operation. The training procedure is as follows: first each single operation is split in basic motions. Then the human model is trained to perform the basic motions by using specific commands of the programming language (i.e. reach, grasp, put, release, move, etc). Note that such phase usually requires a huge effort due to the high number of basic motions of each operation. Moreover eM-Workplace requires information regarding working postures at the beginning and end of each lifting task, frequency and duration of lifting tasks, process and set-up times of operations not performed by human models.

3.3. Validation phase

The last step of the simulation model development is the *validation* that aims at determining if the simulation model is an accurate representation of the real manufacturing system workstation.

The authors propose a 2-step validation phase. The first step aims at analyzing and discussing the simulation model with the workers and employees of the manufacturing system. In effect the

Fig. 2. Real and virtual Assembly workstation, real and virtual Pressure test workstation.

validation of a simulation model devoted to support a methodology for the effective ergonomic design of manufacturing system workstations has to consider the advices and suggestions of the operators directly and daily involved in the production process. With the help of the workers the authors checked all the basic motions of the human models and deleted some errors concerning the work methods (wrong working postures, wrong motions or redundant motions). At the end of this phase the simulation model was "reasonable" both to workers, company's engineers and technicians for its capability to recreate correctly the workplace layout and all the manufacturing operations as well.

The second step of the validation phase aims at comparing the real process time and the time obtained using the simulation model, both required for completing the same Shop Order. The authors take into consideration a typical Shop Order that requires the production of 12 medium section hydraulic hoses. The real process time for completing the Shop Order is available from the company informative system (as mentioned in "The Manufacturing System" section, at the end of each operation the worker sets the status "end operation" on the company information system recording the process time). Table 3 consists of real process times (collected from the company informative system) and simulated process times (evaluated by using the simulation model). For each workstation the error in terms of difference between real time and simulation time does not exceed the 6.0% that means the simulation model is capable of recreating the manufacturing system behaviour with satisfactory accuracy.

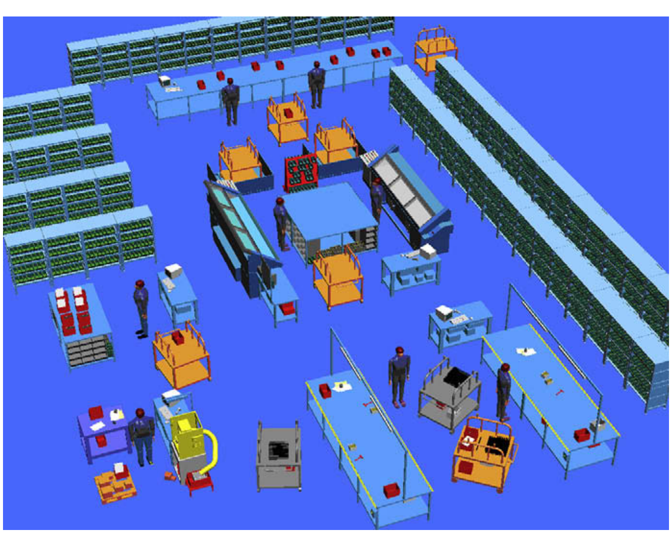

Fig. 3. Virtual Assembly area.

4. Multiple design parameters, experiments planning and performance measures

The main goal of the paper is to propose a methodology for achieving the effective ergonomic design of workstations within industrial plants (in particular in this case the methodology is applied to a manufacturing system). As already stated in the

Table 2
Data collection for human models characterization.

Operator ID	Age	Gender	Height (cm)	Weight (kg)	Workstation
Op-1	36	male	174	71	Preparation
Op-2	45	male	165	74	Seal Press
Op-3	38	male	183	85	Cutting
Op-4	40	male	179	82	Cutting
Op-5	32	male	175	78	Skinning
Op-6	27	male	181	78	Skinning
Op-7	34	male	177	82	Assembly
Op-8	52	male	175	79	Assembly
Op-9	43	male	174	73	Stapling
Op-10	35	male	175	76	Stapling
Op-11	48	male	176	81	Pressure test
Op-12	51	male	173	76	Pressure test
Op-13	29	male	176	70	Check and packaging
Op-14	37	male	169	71	Check and packaging

Table 3
Simulation model validation: comparison between real process times and simulated process times.

	Preparation	Seal Press	Cutting	Skinning	Assembly	Stapling	Pressure test	Packaging
Process Time [s]	321.50	446.00	1057.70	781.90	1055.40	817.70	913.78	835.6
Simulation time [s]	340.25	470.32	1118.36	823.89	1120.43	864.19	961.50	881.47
Error [%]	5.51%	5.17%	5.42%	5.10%	5.80%	5.38%	4.96%	5.20%

previous section due to the high number of design parameters and performance measures involved in the design of manufacturing systems' workstations, the methodology proposed is supported by a simulation model that recreates the workstations in a 3-D virtual environment. In particular the ergonomic effective design of the workstations is achieved by using the simulation model for comparing workstations' alternative configurations. The generation of the alternative configurations comes out from the variation of multiple design parameters that affect multiple performance measures (ergonomic and time performance measures).

The quantitative evaluation of the effects of the multiple design parameters on the multiple performance measures is achieved by using the Design of Experiments (DOE). Such evaluation allows to choose the final configuration of the workstation.

In the sequel the authors apply the design methodology and define the design parameters, the performance measures and the experiment planning for the manufacturing system workstations characterized by the lowest performance levels: the assembly workstation and the pressure test workstation. In particular, each design parameter (called also factor) is characterized by different levels and generates a comprehensive set of workstation alternative configurations (in terms of workstation layout and tools disposition). In addition to both the workstations a Shop Order made up by 12 medium section hydraulic hoses characterizes all the scenarios.

Sections 4.1 and 4.2 respectively describe the design factors and the performance measures for both the assembly and the pressure test workstations.

4.1. Design parameters definition

At this stage, the methodology requires as first step, a preliminary analysis for detecting, in each workstation, the design parameters (factors) that could have an impact on the workstation performance (ergonomic and time performance). The preliminary analysis shows that distances and angles (associated to objects and tools) could be significant factors for the Assembly workstations. Concerning the Pressure Test workstation, distances and angles associated to objects and tools cannot be easily modified (because the pressure test on the hydraulic hoses is executed by using an automated machine). Consequently the authors decided to consider, as design parameters, four different work methods.

The factors definition for the Assembly workstation is as follows:

- Let β be the *worktable angle*; it defines the orientation of the worktable respect to the actual position (see Fig. 4);
- Let sp be the *air blower position*; it defines the position of the air blower equipment respect to the actual position (see Fig. 4);
- Let cp be the *computer position*; it defines the position of the computer respect to the actual position (see Fig. 4).

The factors definition for the Pressure Test workstation considers four different operators' work methods, each one characterized by a different number of hydraulic hoses to be simultaneously tested. By using the first work method the operator executes the pressure test on a single hydraulic hose, by using the second work method, the operator executes the pressure test simultaneously on two hydraulic hoses, by using the third work method on three hydraulic hoses and by using the fourth on four hydraulic hoses. Fig. 5 shows the actual configuration of the Pressure Test workstation.

Table 4 consists of factors and levels for the Assembly workstation. The factors levels combination generates 8 different configurations; by considering the 4 alternative work methods for the Pressure Test workstation, the Design of Experiments comes up

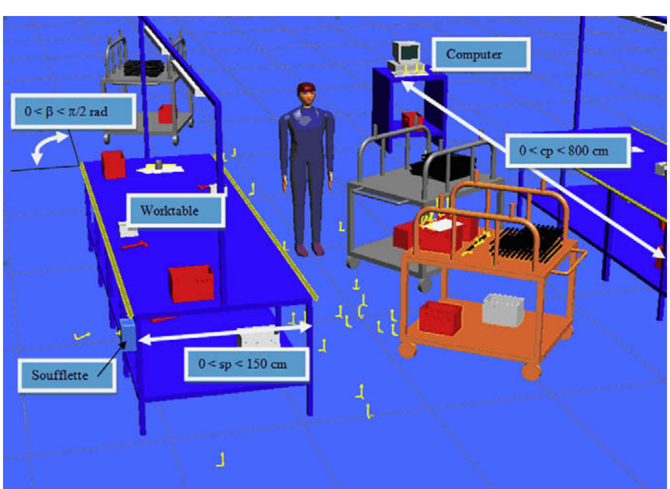

Fig. 4. Actual configuration of the Assembly workstation (with design parameters).

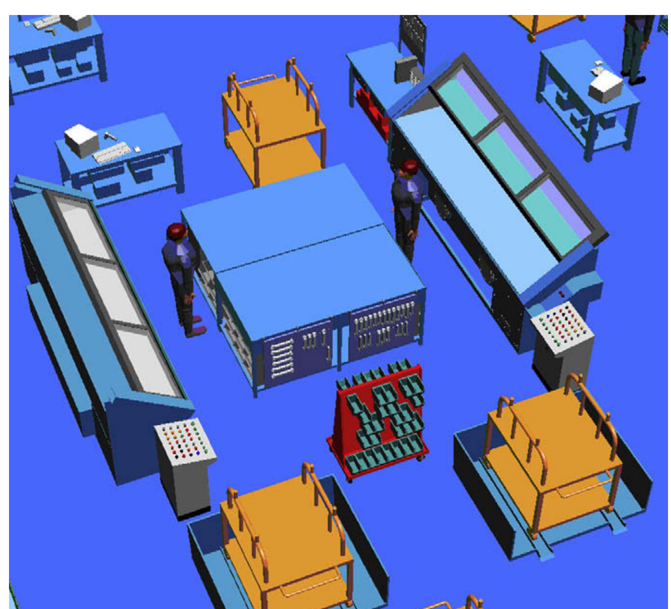

Fig. 5. Actual configuration of the Pressure Test workstation.

Table 4
Design parameters and levels of the Assembly workstation.

Factors	Factor ID	Level 1	Level 2
Worktable Angle (rad)	β	0	$\pi/2$
Air blower (cm)	sp	0	150
Computer Position (cm)	cp	0	800

with 12 different configurations to be tested with the simulation model.

4.2. Performance measures definition

As stated before the design methodology is based on multiple ergonomic and time performance measures. The ergonomic performance measures (based on ergonomic standards) are the lift indexes (evaluated by using the Burandt–Schultetus analysis), the stress levels associated to working postures (evaluated by using the OWAS analysis) and the energy expenditure associated to each activity (evaluated by using the Garg analysis).

The time performance measure is the process time (evaluated by using the Method Time Measurement methodology).

The Burandt–Schultetus analysis (Schultetus, 1980) calculates the maximum weight that a working person can lift (maximum permissible force). To this end, the method requires several input parameters regarding the health conditions, age and gender of the worker, the load weight, the lifting frequency (measured in lifts per minute) and the total task duration. The maximum permissible force is then compared to the actual force being exerted generating three different cases:

- Case 1: the maximum permissible limit exceeds the actual force (an ergonomic intervention is required);
- Case 2: the maximum permissible limit is equal to the actual force (a corrective intervention is necessary in the near future);
- Case 3: the actual force is lower than the maximum permissible force (no ergonomic intervention is required).

The OWAS (Ovako Working Posture Analysis) method carries out a quantitative analysis of body postures occurring during the work processes (Kharu et al., 1977, 1981). It records the stress associated to each body posture. According to the OWAS, each body posture the worker assumes is classified in one of four stress categories:

- Category 1: the body posture has no adverse effects on the muscular system of the worker; the stress level is optimum, no corrective interventions are required;
- Category 2: the body posture should have adverse effects on the muscular system of the worker; the stress level is almost acceptable, corrective interventions are required in the near future;

Table 5
Simulation results for the Assembly workstation.

Assembly Workstation				
β	sp	cp	MTM-1	Garg
			Process Time (s)	Energy Expenditure (kcal)
0	0	0	1118.36	1736.0
0	0	800	1104.64	1701.3
0	150	0	986.66	1466.9
0	150	800	972.94	1432.2
$\pi/2$	0	0	1107.38	1710.0
$\pi/2$	0	800	1096.41	1675.2
$\pi/2$	150	0	975.68	1440.9
$\pi/2$	150	800	964.71	1406.2

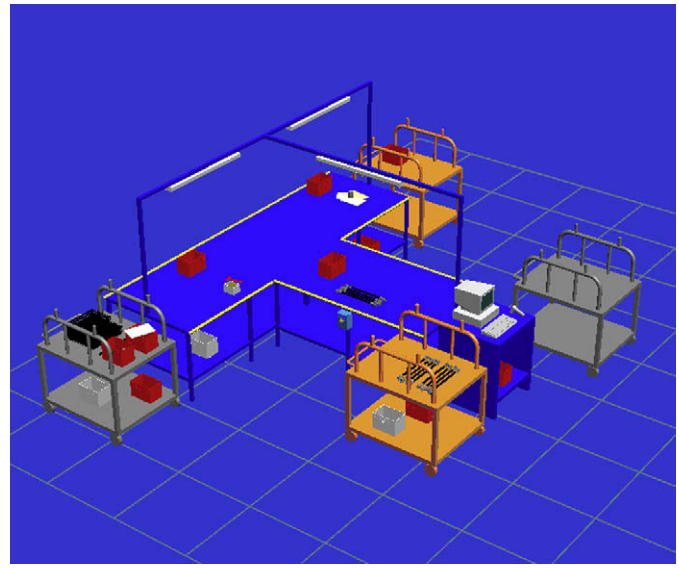

Fig. 6. Effective ergonomic design of the Assembly workstation.

- Category 3: the body posture has adverse effects on the muscular system of the worker; the stress level is high, corrective interventions are required as soon as possible;
- Category 4: the body posture has remarkably adverse effects on the muscular system of the worker; the stress level is very high, corrective interventions are immediately required.

The Garg analysis (Garg, 1976) measures the amount of energy expended during manual activities. The analysis splits a specified activity up into smaller steps calculating for each of them the Energy Expenditure (EE); the sum of the energy associated to each step represents the total Energy Expenditure for the activity. As input parameters, such analysis requires information concerning body weight and gender of the worker, load weight, lifting frequency (measured in lift per minute).

Consider now the process time (PT), as before mentioned, the simulation model uses the MTM for evaluating the process time of each operation. The official definition of the Method Time Measurement methodology is: “a procedure which analyzes any manual operation or method into the basic motions required to perform it and assigns to each motion a predetermined time standard which is determined by the nature of the motion and the conditions under which it is made” (Maynard et al., 1948). The MTM-1 decomposes a generic operation in a set of basic motions (i.e. reach, move, grasp, release, etc.); to each basic motion, a predetermined time standard is associated (note that each basic motion is characterized by a set of different cases). The total time required for performing the operation is the sum of the time standards associated to each basic motion.

5. Workstations ergonomic effective design

In this section the authors propose the application of the methodology and achieve the ergonomic effective design of both the Assembly workstation and the Pressure Test workstation.

In particular the authors use the simulation model for comparing the workstations’ alternative configurations obtained by considering all the factors levels combinations (see Section 4.1). The multiple performance measures defined in Section 4.2 allow to choose the workstations’ final configuration.

Table 6
Simulated times for each macro-activity in the Pressure Test workstation.

Pressure Test Workstation	1 Hose	2 Hoses	3 Hoses	4 Hoses
Macro-activity 1	4.89	5.32	7.12	8.25
Macro-activity 2	26.86	36.75	50.53	68.13
Macro-activity 3	15.70	14.44	13.28	14.36
Macro-activity 4	29.06	39.07	54.57	74.54
Macro-activity 5	31.06	45.54	60.61	80.88
Macro-activity 6	19.96	23.36	25.37	26.28
Total (s)	127.53	164.48	211.48	272.45

Consider now the Assembly workstation. The activities performed by the operators do not require heavy lifting tasks or uncomfortable working postures. In effect, the Burandt–Schultetus analysis and the OWAS do not reveal any particular lifting or posture problem. Significant results for the effective ergonomic design have been obtained in terms of Energy Expenditure (EE) and Process Time (PT) respectively for the Garg and MTM analyses. Table 5 reports simulation results for each factors levels combination.

The variation of the worktable angle β ($0 < \beta < \pi/2$, considering fixed the remaining factors levels) affects both the EE and the PT. Note the reduction of the EE and the PT in the case of $\beta = \pi/2$ (EE = 1710.0 kcal and PT = 1107.39 s reductions respectively 1.5% and 1.0%). The variation of the air blower position (sp) and the computer position (cp) shows a similar behaviour in terms of the EE and the PT. The variation of the sp causes a reduction of both the EE and the PT (EE = 1466.9 kcal, PT = 986.66 s reductions respectively 15.5% and 11.8%). Similarly the variation of the cp causes a reduction of both the EE and the PT (EE = 1701.3 kcal, PT = 1104.64 s reductions respectively 2.0% and 1.2%). The results in Table 5 show that such positive effects are amplified by the interaction among the factors levels (i.e. the interaction between the sp and the cp causes a reduction of the EE and the PT respectively equals to 17.5% and 13.0%). The variation of all the factors levels guarantees the best workstation performances both in terms of ergonomics and work measurement (EE = 1406.2 kcal, PT = 964.71 s reductions respectively 19.0% and 13.7%). The process time reduction guarantees higher productivity levels: 49 additional hydraulic hoses per day (1083 additional hoses per month).

Concerning the final configuration of the assembly workstation, the design methodology suggests the following interventions (respect to the actual configuration): (i) a T-shape configuration for the worktable (one operator at each side); (ii) a computer position closer to the worktable and (iii) an air blower position closer to the area of the worktable where the hoses are assembled. Fig. 6 shows the final configuration of the assembly workstation (effective ergonomic design).

Consider now the Pressure Test workstation. The operations performed in this workstation have been subdivided into 6 different groups (each group has to be regarded as a macro-activity), described as follows.

- *Macro-activity 1* – the operator sets the workstation for starting the testing operations.
- *Macro-activity 2* – the operator prepares the hydraulic hoses to be tested.
- *Macro-activity 3* – the operator moves the hydraulic hoses from the worktable to the testing machine.
- *Macro-activity 4* – the operator connects the hydraulic hoses to the testing machine, performs the security procedures and starts the testing phase.
- *Macro-activity 5* – after the test the operator performs the visual checks and moves the hoses on the worktable.
- *Macro-activity 6* – the operator completes the Shop Order.

Table 6 consists of process times for each macro-activity (expressed in seconds and evaluated by using the MTM-1 analysis).

The authors suppose to subdivide the macro-activities into two different categories: preparation operations (performed just once for the entire Shop Order) and cyclic operations (cyclically performed for each hydraulic hose). The macro-activities 1 and 6 (workstation set-up and Shop Order completion) belong to the first category. The macro-activities 3–5 belong to the second category. Note that the frequency of such macro-activities depends on the work method used by the operator. The macro-activity 2 is cyclically performed but the process time of the macro-activity 2 affects the Shop Order total completion time just once (in other words it is cyclically repeated during the macro-activity 4). Therefore, the macro-activity 2 should be inserted in the first category and considered as preparation time.

Consider now the four different work methods in terms of hydraulic hoses simultaneously tested: one single hydraulic hose (scenario 1) two, three or four hoses simultaneously tested (respectively scenario 2, scenario 3 and scenario 4) by taking into consideration a Shop Order made up by 12 hydraulic hoses. As in the case of the Assembly workstations, for each scenario the Burandt–Schultetus analysis and the OWAS do not reveal any

Table 7
MTM and Garg analysis results for the Pressure Test workstation.

Preparation				
	Macro-Activity 1 (s)	Macro-Activity 2 (s)	Macro-Activity 6 (s)	Total Preparation time (s)
Sc1	4.9	26.9	20.0	51.7
Sc2	5.3	36.7	23.4	65.4
Sc3	7.1	50.5	25.4	83.0
Sc4	8.3	68.1	26.3	102.7
Cyclic				
	Macro-Activity 3 (s)	Macro-Activity 4 (s)	Macro-Activity 5 (s)	Total working time (s)
Sc1	188.4	348.7	372.7	909.8
Sc2	86.7	234.4	273.2	594.3
Sc3	53.1	218.3	242.5	513.9
Sc4	43.1	223.6	242.7	509.3
		Energy Expenditure (kcal)		Total Time for completing the Shop Order (s)
Total Time – Scenario 1		2165.67		961.5
Total Time – Scenario 2		1521.95		659.7
Total Time – Scenario 3		1504.93		596.9
Total Time – Scenario 4		1644.84		612.0

particular lifting or posture problem. However, also in this case, the Garg and MTM analyses give significant results that can be used for the ergonomic effective design of the workstation (in terms of energy expenditure, EE, and process time, PT). Table 7 consists of the MTM and Garg analysis results for each scenario. Table 7 reports the PT (in seconds) for preparation operations (macro-activities 1, 2 and 6) and for cyclic operations (macro-activities 3–5). In addition, the last 4 rows of Table 7 report the total amount of energy expended for each scenario (EE) and the total time required for completing the Shop Order. The optimal work method in terms of EE is the third scenario. In particular the amount of energy expended for completing the Shop Orders is 1504.06 kcal.

The third scenario (three hydraulic hoses simultaneously tested) is also characterized by the minimum Shop Order PT. In this case the total PT is 596.9 s (about 9 min and 57 s). Note that the PT improvement is about 38% respect to the first scenario, 9.6% respect to the second scenario and 2.5% respect to the fourth scenario. As in the case of the assembly workstation the methodology proposed by the authors allows to achieve the effective ergonomic design of the workstation both in terms of energy expenditure and process time.

6. Conclusions

The paper proposes a methodology for the ergonomic effective design of workstations within industrial plants. The methodology is proposed to the reader contextually to its application to a real industrial plant that manufactures high-pressure hydraulic hoses. The design methodology compares the actual workstations with alternative configurations by carrying out specific analysis supported by a well-planned experimental design (based on multiple design factors and multiple performance measures). The experiments running are supported by a simulation model that recreates in a 3-D virtual environment the workstations belonging to the industrial plant. The simulation model is developed by using the CAD software Pro-Engineer and the simulation software eM-Workplace. By applying the methodology, the authors achieve the effective ergonomic design of the Assembly and Pressure Test workstations. For each workstation the methodology requires to define multiple design parameters: objects distances and angles for the Assembly workstation and four different work methods for the Pressure Test workstation.

Concerning the Assembly workstation, the methodology allows to evaluate the impact of each design parameter on multiple performance measures (the Permissible Force related to lifting activities, the Stress Level related to working postures, the Energy Expenditure and the Process Time). The final result is the ergonomic effective design of the assembly workstation: a completely new workstation layout characterized by several ergonomic improvements in terms of energy expenditure and process time.

The ergonomic effective design has been achieved also for the Pressure Test workstation by choosing the best work method in terms of hydraulic hoses to be simultaneously tested.

Finally note that the authors propose a design methodology capable of maintaining its validity for different workstations and different manufacturing systems. In effect the methodology is based on a number of steps that starting from the implementation of a simulation model of the real workstation allows the definition of multiple design parameters, the observation of the effects of such parameters on multiple ergonomic and time performance measures (by using the Design of Experiments) and the definition of the workstation final configuration (effective ergonomic design). Furthermore the use of the DOE is the first step toward the introduction of optimization techniques for the ergonomic effective design of the manufacturing system workstations.

Further researches are still on going (in cooperation with the same manufacturing system) for analyzing the remaining workstations of the Assembly area and the workstations of the Mechanical area.

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