AN OVERALL DHM-BASED ERGONOMIC AND OPERATIONIAL ASSESSMENT OF A MANUFACTURING TASK: A CASE STUDY

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ABSTRACT

An effective manufacturing workstation design should jointly consider both operational and ergonomic characteristics. Accordingly, the desirability of candidate solutions should rely on the definition and combined assessment of multiple Key Performance Indicators (KPIs). Digital Human Modelling and Simulation (DHMS) provides with a powerful tool capable to precisely recreate and assess human tasks in terms of single and separately treated performance measures. However, the lack of consensus in the adoption of ergonomic parameters and the need of integrating methods have been reported as a fundamental shortcoming when conducting an overall systematic data results analysis. Under an engineering approach, we propose the employment of a control chart integrating biomechanical, postural and operational performance indicators in a continuous framework as well as a Desirability Function (DF) allowing the comparison of several alternative designs. A DHMS-based case study of a manual task in the natural roofing slate manufacturing process is presented.

Keywords: Workplace Design, DHMS, Desirability Function

1. INTRODUCTION

During the design of new manufacturing workstations or even in the case of re-design of existing workstations several issues need to be simultaneously considered. As a consequence, workstation effective ergonomic design and productivity enhancement usually require the definition and use of multiple Key Performance Indicators (KPIs).

The development of the Digital Human Modelling and Simulation (DHMS) and its further integration in computer aided manufacturing environments represents the most relevant achievement for the efficient and complete consideration of human factors in production systems. However, DHMS alone is not enough in manufacturing ergonomics, because it does not provide appropriate methods for an overall ergonomic risk assessment (Fritzsche, 2010).

However, some authors have coped with the need of definition and integration of multiple KPIs (Wright and Haslam, 1999; Russell et al., 2007) and also proposing multiple objective functions (Ben Gal and Bukchin, 2002). The above reported references reveal a lack of consensus in the adoption of ergonomic standards or methods. All of this turns out in a confounding panorama for fresh engineers striving to incorporate the ergonomic component into their designs.

It is in the aim of this paper to describe an overall analysis methodology for manufacturing workstations design and re-design. It consists of a task characterization control chart gathering ergonomic and operational KPIs within a continuous framework. This will be used as the basis of an expert-driven design. A desirability function is then used for quantifying the alternatives and supporting a reasonable choice. This methodology has been specifically designed to the slate splitter's task in the context of an improvement study (del Rio et al., 2009; Rego et al., 2010), although it can be adapted and extended to other kind of tasks.

On section 2, some initial considerations are made before explaining the general methodology on section 3. This methodology application and its results are described on section 4.

2. PROCESS AND STUDY CONSIDERATIONS

Spanish slate sector for roofing applications is mostly composed of small and medium enterprises (SMEs). The manufacturing process relies on highly labour-intensive activities and more specifically on the mastery of a specialized group of workers known as Splitters. Final product quality, plant's costs and productivity depend largely on their individual performance. Since a lot of repetitive and potentially hazardous movements have to be made there is a substantial risk of developing musculoskeletal disorders (MSDs).

Generally, when dealing with a workstation design some of the following restrictions have to be considered:

- *Financial*. Companies cannot stop their production in order to test new workplace alternatives. In that sense, SMEs are even more sensitive. A practical, quick, but effective approach is appropriate for SMEs which will lead to good results with affordable resources.
- *Technological*. Major changes in the structure of the task are not plausible unless a new automated concept approach is adopted.
- *Process Integration*. Upstream and downstream process parameters should not be altered. Changes

implemented under a myopic and local optimization perspective may decrease the global performance of the plant.

In the splitting case, all of them are found. Accordingly, a simple, quick and cheap video-based data collection is used in order to determine the set of postures and times which the worker usually performs. After a detailed input data analysis, the modelling process may start by reproducing a virtual environment assuring the geometric and operational similarity. The DHM-VE Delmia V5R19 allows a high level of detail in defining the exact sequence of movements even for hands and fingers.

Regarding the analysis stage, Delmia V5R19 provides with a Biomechanical Analysis model, reporting the spinal compression and joint shear forces (L4/L5), among others. Also RULA can be applied to each posture of which a task is made of. Cycle time can be obtained from the Delmia task time estimation and the statistical frequency analysis (from video-recording observation). Energy expenditure is also provided by the specific Delmia tool. More details of the modelling procedure can be found in Rego et al. (2010).

3. ANALYSIS METHODOLOGY

The analysis methodology is depicted in Figure 1. There are two parallel processes, the modelling and simulation typical stages (left part of the schema) and the results treatment (the right part). According to the study goals, quantitative KPIs have been defined. Usually, those goals are operational -improving the system productivity or reducing the cycle time- and ergonomic -reducing the injuries risk or improving the working environment-. In the splitters case, the aim is to improve the ergonomic conditions while maximizing the throughput rate. Accordingly, we have defined the following set of key performance indicators (Table 1).

Table 1: KPI definition

KPIs	Explanation
Postural Risk Assessment (P)	The worker's posture is assessed during the task according to RULA. It is especially thought for the assessment of tasks that mainly imply the upper limbs as is the splitters case
Biomechanical Risk For Injury (B)	The Spine Compression value is a complementary measure of risk of MSDs. According to NIOSH guidelines, compression force on the intervertebral disk over 3.4 kN may eventually lead to injuries
Energy Expenditure (E)	The metabolic energy consumption is included, according to Garg guidelines. It is a physiological measure to the amount of effort spent on the task
Cycle Time (T)	It is a measure of the worker's throughput rate

Those KPIs can be either local –a different value for each posture of which a subtask is composed of- or global –a single KPI value for each subtask-. For instance, in the case study, postural risk and L4/L5 spine compression are local KPIs, because they have an evolution over time. On the contrary, time and energy expenditure are global KPIs. Also the goals should be accounted in order to set priorities between KPIs.

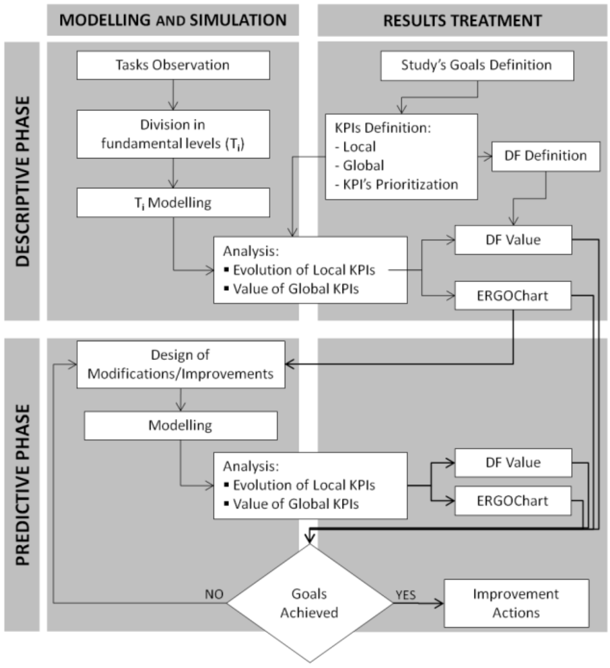


Figure 1: General Methodology for the Overall Analysis

Regarding the M&S part of the schema, present conditions are considered in the "descriptive model". In the case of an early design, this descriptive model is just the initial scenario, but in the case of an existing task, it represents real events so that a validation phase is necessary. In any case, the work cycle will be divided in fundamental subtasks and then modelled. In the splitter's case, those subtasks consist on successively receiving the block, performing a rough initial cutting, executing three possible types of splitting and finally, three classifying subtasks. Each subtask will provide with a huge amount data (postural risk and spine load for each posture; time and energy expenditure). The resulting data will be graphically arranged into a fictitious time axis and tables and compared to some reference values (ERGOChart). An example is shown in Figure 2. We refer to a fictitious time because the fundamental tasks can occur more than once so that the global cycle time does not correspond with the addition of each single subtask. This chart shows the postural and biomechanical risk evolution over time, in comparison with the maximum recommended values. Also, as complementary information, an energy expenditure table is shown. The use of the overall chart makes it possible to know the ergonomic and operational features of every posture all along the normal operations. This continuous analysis also enables finding "when" worst posture takes place.

As a result, it can be used for driving design efforts to reduce ergonomic impact and/or increase performance in specific harmful movements or operations. Designs coming from the first model are then implemented in a second model generating new data postures results that will shape a second ERGOChart. This iterative process finishes when the study goals are achieved. However, a local improvement in one single KPI could worsen other KPIs. The desirability function (DF) has been designed to assess the whole task by integrating the defined KPIs accounting for the impact of a specific movement in the complete work cycle. Besides, as opposite to the chart, it represents a quantitative general improvement so comparison between candidate solutions is allowed.

The concept of desirability, introduced by Harrington (1965), is a method for multicriteria optimization in industrial quality management. Via desirability functions (DFs), which allow for comparing different scales of the quality measures (QMs) by mapping them to a [0, 1] interval and the desirability index (DI), the multivariate optimization problem is converted into a univariate one (Trautmann and Weihs, 2005).

As suggested in Ben Gal and Bukchin (2001), a KPI-based desirability function can be developed for a multi-objective design of workstations. The desirability is a geometric average of the individual factors, given a particular weight (exponents, *a, b, c* and *d*):

$$D = (P'^{a} \cdot B'^{b} \cdot E'^{c} \cdot T'^{d})^{\frac{1}{a+b+c+d}} \qquad (1)$$

P', B', E' and *T'* are the [0, 1] normalised values of the KPI values for postural risk, biomechanical features, energy expenditure and cycle time.

Yet an important limitation of this overall methodology is that the models are not parameterized, the proposed ad hoc simulation-driven experimentation is adequate for assessing a whole set of design solutions for which parameterization would become unaffordable. Although a functional optimization is not reachable, important improvements may be attained. Were these exact models parameterized, an optimization approach could be adopted. Some examples in the literature go in that direction (Ambrosse et al., 2002 and Longo and Mirabelli, 2009). In these cases, by means of a DOE methodology different scenarios are automatically analysed. Ben Gal and Bukchin (2002) go a step further by optimising the best solution using Response Surface Methodology (RSM). Nevertheless, a biasing shortcoming arises as only geometrical factors adopting deterministic values are considered in all cases. As well as being fit-for-purpose in the case study, the non parameterized experimentation allows more comprehensive and tailored design alternatives (not only geometric variables).

4. CASE STUDY: METHODOLOGY AND RESULTS

As above defined, desirability is a geometric average of KPIs. In Table 2, they are defined and explained.

Table 2: KPIs for the Desirability Function.

KPI (Formula)	Explanation
Postural Risk $P = \frac{APR + MPR}{2}$	APR/MPR are the average/maximal postural risk over the whole cycle-composed set of postures.
Biomechanical Results $B = \frac{ABR + MBR}{2}$	ABR/MBR are the average/maximal biomechanical result of the spine compression
Energy Expenditure E (kcal/min)	Garg Equation Result, obtained directly from the DHM energy expenditure analysis
Cycle Time T (s)	Cycle time, addition of the different subtasks a complete cycle is made up.

The reason for considering not only the average postural risk / biomechanical results but also their maximum values is that the average is related to a cumulative exposure whereas the maximum provides the information of peak values, so the complete risk of reporting MSD is taken into account.

The values of a, b, c and d are set according with the type of task and the project's goals. In this case, we have considered the following priority factors:

- Reducing the postural risk (a=4)
- Reducing the cycle time (d=3)
- Reducing the biomechanical exposure (b=2)
- Reducing the energy expenditure (c=1)

In our study, the ergonomic improvement has slight priority over the throughput rate maximization. Also, we consider that the ergonomic improvement is better represented by the RULA postural risk. RULA is a well known and widely used ergonomic assessment method and it is especially thought for the assessment of tasks that mainly imply the upper limbs as is the splitters case. Since the throughput rate is also important, the following factor in priority is the cycle time. Finally, the other two factors have been ordered according to the same priority criteria, i.e., third the biomechanical exposure and finally the energy expenditure.

4.1. SCENARIO H1. Present Conditions

4.1.1. Modelling process

A typical Splitters' work cycle is made up by the following stages:

- Previous Operations: it includes the block reception and the preparation for the operation (T1).
- Rough Splitting: the block is divided into a variable number of pieces depending on its quality and size, by using chisel and hammer (T2).
- Splitting: a variable number of thin plates are obtained by dividing the pieces split in the previous task. Three main situations have been characterized and simulated, i.e., no turning (T3), turning (T4), and rejecting the final plate (T5).
- Sorting and cleaning: sorting depends on the number and quality of the plates. It usually involves lifting tasks. Three main situations have been characterized, i.e., classifying one tile (T6), a group of tiles (T7) and cleaning the workplace (T8).

Each subtask has been modelled by using videos and historical information. Also geometrical data has been incorporated into the models. Figure 1 shows a frame of the model simulation and its equivalent.

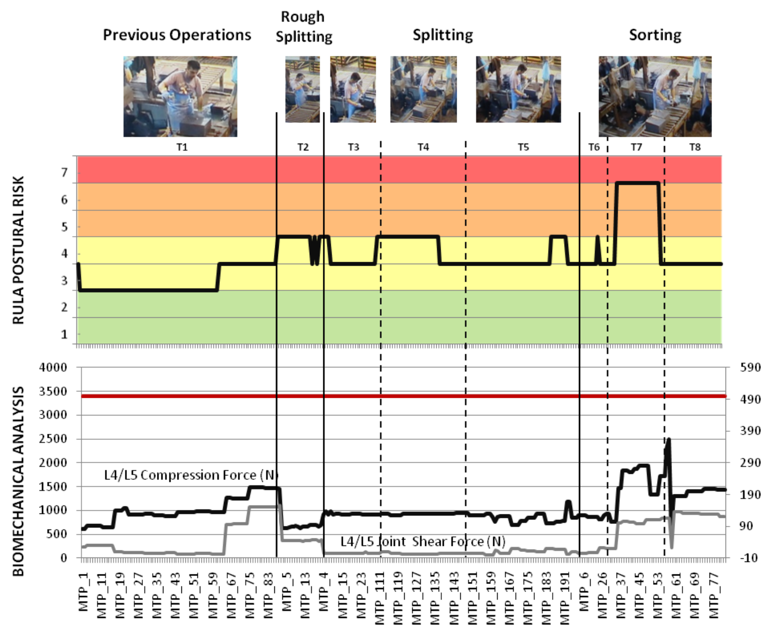
Figure 1. Frame of Previous Operations in H1 Model (up) and its Real Equivalent (down)

4.1.2. ERGOChart

Figure 2 shows, the evolution of the postural risk (upper graph) and the L4/L5 compression and joint shear forces (lower graph) along the cycle. The black line represents the L4/L5 (left axis) and the grey line depicts the joint shear forces together with their respective recommended limits (NIOSH). These threshold values -3400 N and 500 N for the compression and the joint shear forces, respectively- are represented by the same red line on two different scales. On the right, the Energy Expenditure (EE) and the time required (CT) for each subtask are also shown.

4.1.3. Interpretation

The RULA postural risk goes from 1 (green zone, the posture is acceptable) to 7 (red zone, changes are required immediately). As it can be noticed, the highest postural risk is achieved during the sorting tasks. In particular, task T7, carrying a group of plates (6 kg) to the rolling table, reaches score 7. The highest level during the splitting is found during the rejection movements.



OPERATIONAL ANALYSIS		Energy Exp. (kcal)	Time (s)
Previous Ops.	T1	0.41	8.76
Rough Splitting	T2	0.16	2.15
Splitting	T3. No turning	0.19	2.40
	T4. Turning	0.61	4.39
	T5. Reject movement	0.27	2.88
Sorting and cleaning	T6. One tile	0.16	3.70
	T7. Group tiles (6kg)	0.42	8.64
	T8. Cleaning	0.14	3.01

Figure 2. ERGOChart: Ergonomic and Operational Analysis Control Chart

The biomechanical parameters also increased their value during T7. It is remarkable that spine forces also increased at the end of T1, representing the time during the previous operations when the worker bends his back for picking his chisel and hammer from the work surface.

4.2. SCENARIO H2: Modified height

4.2.1. Motivation

While performing their tasks, splitters combine heavy, light and precision work in a continuous series of quick and repetitive movements so that it is very difficult to identify their corresponding shares and so determining a kind of ergonomically workbench height. Besides, as most of them use a pallet to separate from the wet floor, the effect of height on the ergonomic characterization of the actual operation is far from immediate.

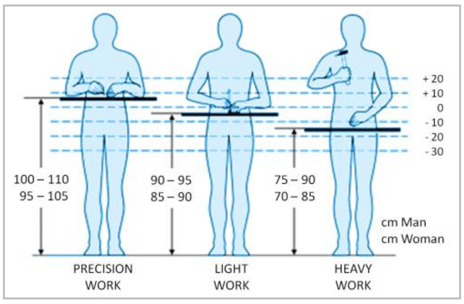


Figure 3: IBV (2011) recommended ranges of optimal workbench heights for precision, light and heavy works

4.2.2. Proposal

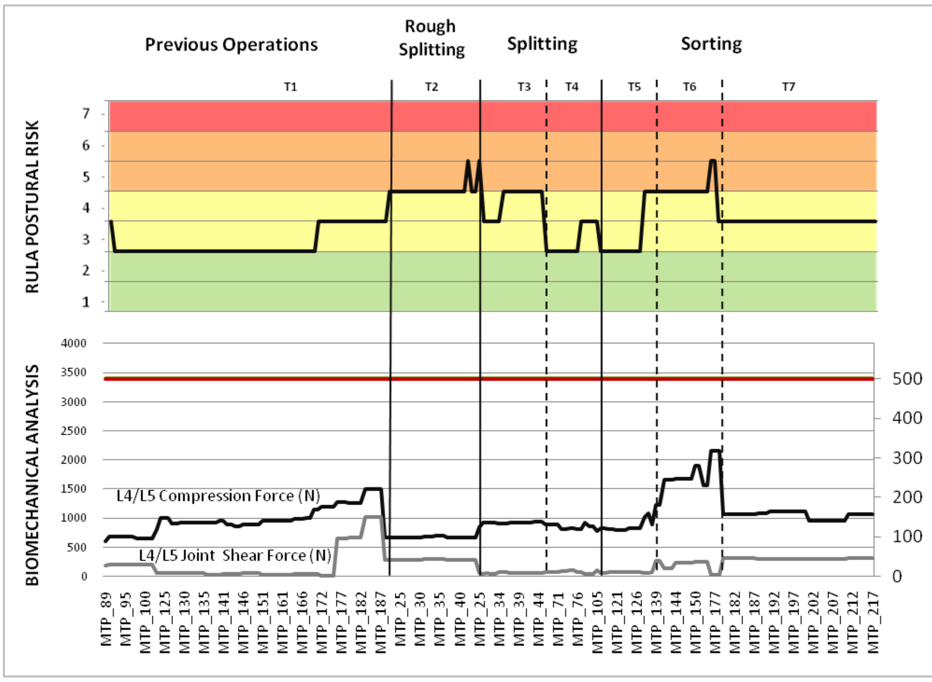
At present, the work surface height would fit with the heavy work recommended one. Every subtask has been re-modelled considering that the workplace is adequate for light work.

4.2.3. ERGOChart

As shown in Figure 3, none of the tasks achieved score 7 in the RULA analysis. Also, compression and joint shear forces decreased 6% and 3% in average (detailed results are shown in table 1). When comparing EE and CT, there is a 13% and 4% reduction, respectively.

4.2.4. Interpretation

In general, it would be better to work under those conditions so we assumed this scenario for further experimentation.



OPERATIONAL ANALYSIS

DETAILED		Energy Exp. (kcal)	Time (s)
Previous Ops.	T1	0.34	8.61
Rough Splitting	T2	0.21	2.73
Splitting	T3. No turning	0.25	3.83
	T4. Reject movement	0.13	1.99
Sorting and cleaning	T5. One tile	0.15	3.19
	T6. Group tiles (6kg)	0.55	6.84
	T7. Cleaning	0.11	3.61

Figure 4. Ergonomic and Operational Analysis under H2 Conditions

4.3. SCENARIO H2 – A. Modified height and frontal rejection movement

4.3.1. Motivation

Both on H1 and H2 ERGOCharts, the postural risk of the reject movement reaches level 5 (changes are needed). In fact, every time the labour has to reject a block, part or plate, he is obliged to make a lifting and twisting movement.

4.3.2. Proposal

Were a connecting conveyor belt to the waste line provided, this highly undesirable movement could be changed for a frontal, safer and faster push movement.

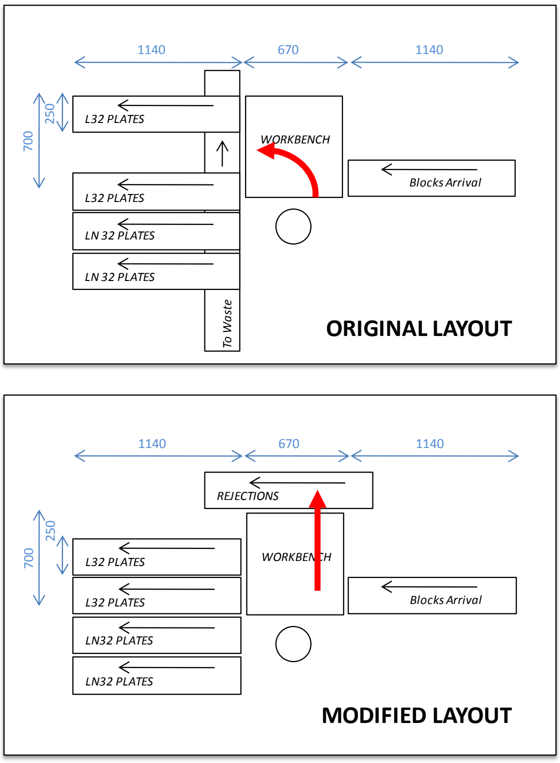


Figure 5: Original and Proposed Layouts.

4.4. SCENARIO H2 – B: Modified height and tool-belt

4.4.1. Motivation

Attending to the H1 and H2 ERGOChart, we can see that the value of postural risk increases from 3 to 4 in both cases at the end of the task. This is because splitters are forced to bend his back whenever they pick their tools from the table. These are unnecessary movements that should be avoided.

4.4.2. Proposal

The employment of tool belts among the splitters, unlike other artisanal professionals, would be a brand new action, not only in this particular company, but in the whole sector. This simple accessory facilitates the work as it ensures comfortable reaching out to take the chisels without the need to bend forward or sideways.

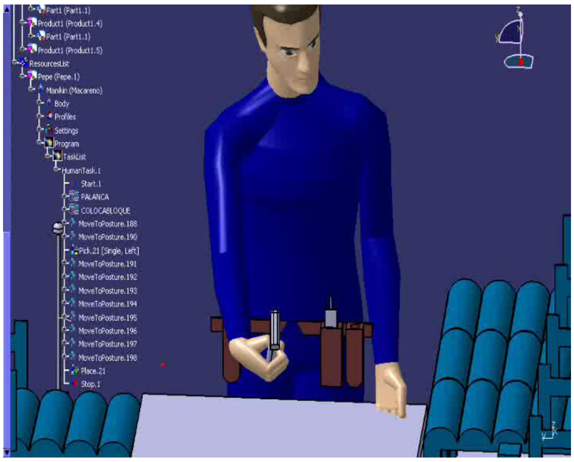


Figure 6. H2 – B Manekin with the toolbelt

4.5. SCENARIO H2 – C: Modified height, radial distribution

4.5.1. Motivation

This initiative is the outcome of a specific design effort aimed at reducing the ergonomic impact and improving productivity of the sorting tasks, which show the highest risk levels.

4.5.2. Proposal

A radial distribution scheme is presented as an innovative conceptual design in this sector. The distribution conveyor belts have been located accordingly to their frequency of use; blocks arrive from the right side of the splitter and rejected materials are this way frontally pushed away, which is a much safer and faster operation.

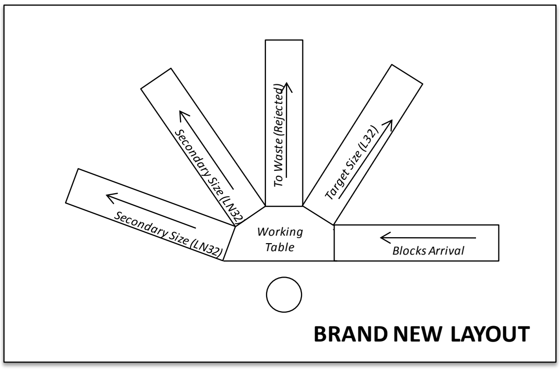


Figure 7. Proposed Layout.

5. DESIRABILITY ASSESSMENT

Table 3 summarizes descriptive (H1) results and the predictive improvement measures (H2, H2-A, H2-B, H2-C) with their corresponding KPI results. As it can be noticed all the proposals improve the ergonomic and the operational parameters. These values have been normalised and introduced in the DF. Results are presented on table 4.

Table 3. KPIs values for the Descriptive and Predictive Models

SUMMARY		H1	H2	H2A	H2B	H2C
T (s)		208.7	181.6	179.4	178.6	176.9
E (kcal/cycle)		13.47	12.88	12.24	12.08	11.70
P	Avg	4.19	3.92	3.90	3.81	3.79
	Max	7	6	6	6	5
B (N)	Avg	1029	993	967	915	894
	Max	2493	2159	2159	2159	1493

Table 4. Normalised KPIs and Desirability Values for each Scenario.

	H1	H2	H2A	H2B	H2C
T'	0,00	0,85	0,92	0,95	1,00
E'	0,00	0,33	0,69	0,79	1,00
P'	0,00	0,53	0,54	0,58	1,00
B'	0,00	0,33	0,35	0,39	1,00
D*	0,00	0,40	0,53	0,59	1,00

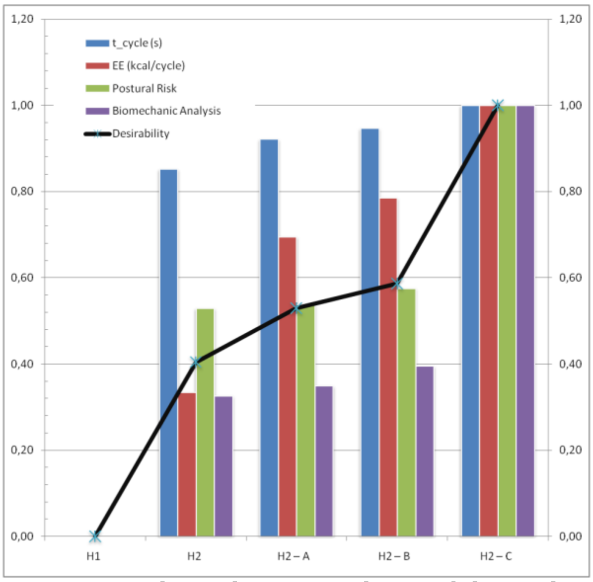


Figure 8: Final Results: KPI and Desirability Values for the Proposed Workplace Designs.

Finally, in Figure 8 the different proposals are assessed according to their desirability value. Every configuration is represented by a set of four bars representing T', E', P' and B' values respectively. Besides, the overall score is depicted by the continuous black line. It can be concluded that:

1. It is more convenient to perform the task under light work recommended height -H2- than within a heavy work height range–H1.
2. The employment of tool belts –H2B- would avoid unnecessary back bending whilst increasing productivity.
3. A simple ramp – H2A- would change the sequence of movements required every time a rejection has to be done to a better ergonomically and faster operation.
4. The best alternative is H2-C (radial distribution), especially in terms of biomechanical exposure. However, a feasibility economical analysis should be carried out since upstream and downstream factors would be affected.

6. CONCLUSIONS

A quantitative approach to a combined ergonomic and operational assessment of the slates splitters tasks has been presented by means of a DHMS study.

Under an engineering approach, we propose the employment of a control chart integrating biomechanical, postural and operational performance indicators in a continuous framework. The use of the overall chart allows knowing the ergonomic and operational features of every posture all along the normal operations. Its characterization would be the basis of an expert-driven experimentation stage.

The DF allows assessing the task by integrating both a local change into the whole of the work cycle and a set of KPIs including ergonomic and operational parameters. Such DF value quantifies the level of overall improvement.

This analysis methodology could be easily extended to other manufacturing tasks, especially when there are limited resources or time.

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