**<Left running head>Pereira da Silva, Tortorella, and Amaral Ergonomics
Standpoint for Lean Production in Assembly Cells**

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Psychophysical Demands and Perceived Workload—an Ergonomics Standpoint for Lean Production in Assembly Cells

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Abstract

The adoption of a lean production model means a systematic implementation of various management methods and practices. Such a model presents the human element as a key factor in continuous improvement efforts, influencing workers' job content and the quality of work. However, there are few evidences regarding research on quantitative assessment of the work demand, either psychological or physical, in a lean production environment. Therefore, this study aims to analyze from an ergonomics perspective the psychophysical demand and workers' perceived workload within assembly cells undergoing a lean production implementation. The proposed method integrates complementary concepts of widely known

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techniques, enabling the consolidation of several assessment criteria into one particular index for both psychological and physical demands. Such a diagnostic method is illustrated in a case study from the automotive parts manufacturing sector, whose application is performed in three critical assembly cells selected by senior management. Our findings show systemic gaps between work demand and employees' profile, indicating improvement opportunities in order to provide a better work environment. © 2016 Wiley Periodicals, Inc.

Keywords: Ergonomics; Psychophysical demands; Lean production system; Assembly cells; Framework

1. INTRODUCTION

Any successful enterprise in the current global economy must possess effective and efficient organization of work at the management level (i.e., management and production methods) in order to optimize the work demands and conditions of the workforce and, subsequently, establish the best work practices conducive for maximum human health and productivity and quality of work (Genaidy & Karwowski, 2003; O'Neill, 2005; Yang, Yeh, & Yang, 2012). The adoption of a lean production model means a systematic implementation of various management methods and practices, such as just-in-time manufacture, teamwork, and *jidoka* (Seppala & Klemola, 2004). Lean production model presents the human element as a key factor in continuous improvement efforts. Therefore, it directly influences workers' job content and the quality of work because it provides increased opportunities for participation, worker control, and learning (Getty, 1999). Eklund (2000) demonstrates a clear relationship between work demand (physical and psychological demands) and quality and productivity performance.

Research into ergonomics and working conditions has, for a long time, largely focused on regular production work. However, Backstrand, Bergman, Hogberg, and Moestam (2013) comment that it is important to see ergonomics/human factors as a part of lean production

practices. The lean production model differs radically from the mass production model in terms of the work demands and the work energizers acting on the workers. Theoretically, a true lean production model may tax the workers' muscular, cognitive, and emotional resources to the limit. At the same time, this model must deploy an integrated battery of work energizers to bring compatibility with the muscular, cognitive, and emotional demands. Work energizers may include, among others, task variety, employment security, financial incentives, development and utilization of skills and knowledge, and knowledge of organizational performance (Seppala & Klemola, 2004; Toralla, Falzon, & Morais, 2012).

A work demand may be either physical or psychological, although they are connected with each other and cannot be completely separated when a person is performing a particular task. Moreover, the same task may result in different levels of individual work demands due to human differences in capabilities, efforts, attitudes, cognition, skills, limitations, and states of situational awareness, complacency, fatigue, boredom, anxiety, and stress (Lean & Shan, 2012). Changes in human performance and behavior resulting from psychological demands are closely related to the physiological and biochemical changes in the body, which are based on nervous regulation (Zink, 2000). Furthermore, in evaluating whether a system has a proper design and a reasonable work demand, it is necessary to accumulate evidence that is both quantitative and qualitative nature. Such evidence is accrued from a variety of sources, both engineering and human (MacLeod, 2003).

Literature presents little evidence regarding researches on quantitative assessment of the work demand in a lean production environment. However, there are some data available—from the United States and from Europe—to answer questions about the impact of lean production on job dimensions and health. Production work has been substantially researched in terms of work design (Eklund, 2000; Paez et al., 2004). However, most studies that investigated the health and safety effects of lean production model are in automotive

manufacturing industry (Joseph, 2003; Koukoulaki, 2014; Ulfsfält, Falck, Forsberg, Dahlin, & Eriksson, 2003). In terms of managerial implications, Hagg (2003) discusses different corporate initiatives regarding work demands under lean environments and states that most of them are limited or present significant methodological gaps, entailing poor analysis and practical results. In fact, few organizations study their operations in detail as long as they appear to be working satisfactorily (Beevis, 2003).

Furthermore, the relation between the work demand and worker health is not known under the lean production environment. Such information is vital to assess the best human performance practices that promote the optimum worker health, productivity and work quality. Genaidy and Karwowski (2003) affirm that research on human performance in lean production environments has been hampered by the inadequacies of prior studies both from theoretical and methodological standpoints. Beevis (2003) mentions that the concerns about commercial confidentiality and the cost of the necessary data collection and analysis effort are also disincentives to developing case studies. Therefore, the best human performance practices are yet to be established in a lean production environment.

This study aims to develop a framework that enables to identify the main gap between the psychophysical demands and perceived workload within assembly cells undergoing a lean production implementation. The proposed method comprises the integration of complementary approaches, which provides a more robust and holistic analysis, indicating whether the identified demand gaps are systemic or specific, thus prioritizing the improvements. Moreover, because the assessment is performed based on the existent workload balance among workers within the cells, the proposed method allows identifying the psychophysical bottlenecks created with the established standardized work, which usually does not take into account such details (Rother & Harris, 2001). This research is illustrated on a case study carried out in three assembly cells of a Brazilian auto parts manufacturer

company, which has been implementing lean production practices for more than 15 years. Despite the fact that these cells have been continuously exposed to lean practices and improvement activities, they are the ones that manufacture the heaviest components and present the highest level of working complaints in company's medical department. Thus, with the application of the proposed method, it is expected to understand the existent demands and critical issues, so that the improvement opportunities can be addressed.

The contribution of this research is twofold. First, academically, it provides a method that combines assessment of work demand and workers' perceived workload in a unique approach. Such combination fulfills the existent gaps identified in literature because it integrates the psychological and physical aspects from an ergonomics standpoint. Moreover, it enables the measurement of the psychophysical impact of a lean production environment, providing a better comprehension of the ergonomics factors under this context. Second, in managerial terms, the study's outcomes allow the establishment of a psychophysical demand map for the company's workstations, indicating critical points for improvement in medium and long terms. In a short-term view, this map also supports management in directing the labor force distribution according to workers' profile, in order to minimize working issues and complaints.

2. PHYSICAL AND PSYCHOLOGICAL RISKS IN A LEAN PRODUCTION ENVIRONMENT

The identification of lean and its consequences for human performance is further complicated by the fact that the possible consequences of lean will also be related to the context and its implementation (Vieira, Balbinotti, Varasquin, & Gontijo, 2012; S. Womack, Armstrong, & Liker, 2009). It is expected that the context of the workplace will influence the motives for introducing lean, how lean is interpreted, and what aspects of lean are emphasized. If, for instance, industrial relations are hostile with low levels of trust between management and

employees, lean will be approached and shaped quite differently from a situation with high levels of trust and strong collaboration between the two parties (Hasle, 2014).

During the preparation for implementing lean production practices, it is important to identify musculoskeletal disorders (MSDs) and psychological risks and difficulties because many problems can be avoided if they are known right on the initial steps (Maia, Alves, & Leao, 2013). Koukoulaki (2014) examines the effects of lean production practices on MSDs, stress, and associated risk factors. Work-related MSDs cover a wide range of inflammatory and degenerative diseases of the locomotor system. Examples of risk factors are repetitive handling at high frequency, awkward and static postures, force exertion, and vibration. Work-related psychological risks concern aspects of the design and management of work and its social and organizational contexts that have the potential for causing psychological or physical harm (Brannmark, 2013). Psychological risks can be influenced by job demands, time pressure, low job control, social relations with superiors and colleagues, and job insecurity (O'Neill, 2000; Rodríguez, Buyens, Van Landeghem, & Lasio, 2016).

Theoretical perspectives on the effects of lean production have evolved through the years. An analysis of trends in lean production and its effects is presented in Table 1. The analysis identifies four time periods in which studies were undertaken when there were different approaches to lean production implementation (Hines, Holweg, & Rich, 2004) and different findings about the effects of these implementations. Sparked by the superior performance achieved by lean producers over the performance of traditional mass production system designs, western manufacturers emulated the shop-floor techniques, the structural parts of lean, but often found it difficult to introduce the organizational culture and mind-set (Resnick & Zanotti, 1997). Many early lean efforts showed specific impact only and fell short of their intended impact on the overall system's performance (Holweg & Pil, 2001). In this awareness period (up to 1990), the main weaknesses of lean production were its automotive

manufacturing-based view and limited appreciation of how to handle variability in demand. The implementation was entirely tool focused and generally neglected the human aspects of the high-performance work system core to the lean manufacturing approach. Therefore, the majority of studies at that time report negative effects related to faster work pace, increased upper limb disorders, and perceived stress (Babson, 1993; Berggren, Bjorkman, & Hollander, 1991; Klein, 1991; Mullarkey, Jackson, & Parker, 1995).

After 1990, there was a gradual widening of focus away from the shop floor, a trend often ignored by omission, error, or design by many detractors. This process of “extension” was also accelerated by the promotion of successful western case emulation by businesses in diverse sectors that had adapted their production systems to include a new design based on “lean principles” (Hines et al., 2004; J. Womack & Jones, 1996). These principles involved the identification of customer value, the management of the value stream, developing the capability to flow production, the use of “pull” mechanisms to support flow of materials at constrained operations, and, finally, the pursuit of perfection through reducing to zero all forms of waste in the production system. Regarding risk factors and health effects, the research focus started to shift from mechanical exposure and health effects, for example, MSDs, to psychosocial risk factors and stress. The findings from these studies are mixed with some job characteristics negatively affected and others positively. The reason behind the shift from negative effects to mixed outcomes might be that the work characteristics that cause MSDs were not so extreme in these manufacturing sectors compared with the automotive industry (Bao, Winkel, Mathiassen, & Shanavaz, 1997; Christmansson, Friden, & Sollerman, 1999; Jackson & Martin, 1996; Parker & Sprigg, 1998; Parker, Wall, & Myers, 1995).

The comprehension evolution on lean production may be summarized as a focus on quality during the literature of the early 1990s, through quality, cost, and delivery (late 1990s), to customer value from 2000 onward, as shown in Table 1. Also, during the mid-1990s, the

value stream concept evolved and was seen to extend beyond manufacturing or the single company, stretching from customer needs right back to raw material sources (Hines & Rich, 1997; Rother & Shook, 1998). This provided the link between lean and the supply chain, as for the first time, the production “pull” was extended beyond the boundary of the single factory to include the up- and downstream partners. Thus, in the last period from 2000 to the present, studies were undertaken in a range of sectors that included service organizations that had gradually started to implement lean practices. The results include both negative and mixed effects. The nature of the effects depends on two factors: 1) the sector (e.g., the automotive industry nearly always shows negative effects) and 2) the way lean practices are implemented (e.g., management decisions on which lean practices to implement and how; Conti, Angelis, Cooper, Faragher, & Gill, 2006; Karia & Asaari, 2006; Leroyer, Kraemer-Heriaud, Marescaux, & Frimat, 2006; Saurin & Ferreira, 2009).

TABLE 1. Literature Trend Analysis on Evolution of Lean Thinking and Its Risk Factors
and Health Effects

3. RESEARCH METHOD

To reach the objectives of this paper, the research method began with a demographical data collection and previous analysis of work processes. This initial assessment supplies practical insights from a real lean systems perspective before the framework was set up. After that, the framework setup was conducted based on three main steps (see Figure 1): 1) defining proper methods for work and worker characteristics assessment, 2) defining the psychophysical demand and workers’ perceived workload criteria, and 3) analyzing gaps and identifying improvement opportunities.

Figure 1 Proposed framework main steps.

3.1. Demographic Data Collection and Previous Analysis of Processes

The first step consists of collecting available data related to processes and workers. With regards to processes, several data may be fundamental for previous analysis of work demand, such as process cycle time, demand, standardized work procedures, layout, weight of manipulated components, number of shifts and employees within the cell, heights and parts handling distances, kind of packaging, existence and frequency of quality inspections, and procedures (Beevis, 2003; Lean & Shan, 2012; Parker & Sprigg, 1998). Regarding workers, it is recommended to gather data, such as accidents and medical records, experience and skill level, age, and working complaints (Eklund, 2000; Leroyer, Kraemer-Heriaud, Marescaux, & Frimat, 2006; MacLeod, 2003). Such demographical and process data are used as the basis for the next step of adaptation and definition of proper psychophysical criteria. Moreover, they can be further exploited in order to verify existent correlations with results obtained in the assessment, and justify them.

3.2. Framework Setup

The next steps comprise the definition of the methods and criteria used in the framework. The framework methods were chosen in order to meet the demands of working conditions and workers' profiles. This was done by combining three different approaches: 1) the RNUR or the job-profile method of Renault (1976), which was developed with the National Control of Factories in France and quantifies general work demands through the analyst (external ergonomist consultant) point of view; 2) NASA Task Load Index (TLX_ (1986), which is a multidimensional scale designed to obtain workload estimates from one or more operators while they are performing a task or immediately afterward; and (iii) General Health

Questionnaire, or GHQ, which is a screening tool to detect those likely to have or be at risk of developing psychological disorder (Goldberg & Hillier, 1979).

The selection and application of these methods were performed by an ergonomist after the first direct observation of the tasks. Also, there was a meeting with some company managers (e.g., production, engineering, safety, occupational health) in order to define their applicability over the studied workplace, considering contextual variables and historical of workers' complaints.

The main workers' perceived workload was analyzed separating psychological and physical criteria. The two methods applied for both criteria were the NASA-TLX and the GHQ. Only three (out of six) NASA-TLX criteria and two (out of five) GHQ criteria were used by the framework. The choice for each criterion that composes the proposed framework was a consequence of applicability and workers' profiles observed at the first step. Regarding the physical perceived workload, we proposed the utilization of criteria *Effort* and *Performance*, both originated from the NASA-TLX method. To assess the psychological perceived workload, criteria *Psychic stress* and *Performance suspicion* from GHQ and *Frustration* from NASA-TLX were applied in the proposed framework. The other criteria from the used methods are likely to be integrated in the framework; however, for our studied context, the contribution of these criteria can be considered negligible. The criteria simplifications were validated through a meeting with the company's senior management team, who were experts on the studied process and, hence, were able to criticize the proposed framework. Table 2 shows the criteria's origin and application description.

The main psychophysical work demands were analyzed separating psychological and physical criteria. The main method applied for both criteria was the RNUR. Out of the 30 existent criteria in the Renault's method, only 6 were applicable for our study: 1) supply-removal, 2) level of alertness, 3) repetitiveness of cycle, 4) work effort, 5) heavy objects

handling, and 6) potential. Table 3 shows the criteria's origin and description. The quantitative levels of these criteria were inverted in relation to the original RNUR methodology. In our framework, values were changed to allow comparisons and gap analysis. In the original methodology, a greater value on a 5-point scale represents a higher work demand. In this framework, the greater the value the lower work demand.

Finally, a comparison between each criterion occurs, quantifying the gaps' magnitude and revealing improvement opportunities. The gap comes from the difference between the criteria and represents an ergonomics indicator of that working situation. The resultant gaps should indicate needed improvement actions. However, these improvement opportunities need to consider not only the gaps but also the initial information of Step 1 and all qualitative information that was gathered through the framework application. Table 4 shows the relationship between criteria and their specific meanings.

<INSERT Table 2 about here>

TABLE 2. Psychological and Physical workers' Perceived Workload Criteria

<Insert Table 3 about here>

TABLE 3. Psychological and Physical Work Demands Criteria

TABLE 4. Relations between Framework Criteria

4. CASE STUDY

4.1. Framework Application

The case study was developed in a southern Brazilian large auto parts manufacturer. Its facilities consist of six manufacturing units, with different processes, such as machining, punching, forming, tempering, painting, and assembling, totaling approximately 1,500 employees. This company started its lean production implementation in 2000 and has widely

trained and implemented several lean practices along the site. Many continuous improvement activities were developed and stimulated by senior management, especially at the assembly unit, which is the final unit before parts expedition, and the one that presents the highest level of manual tasks within the cells. This unit also presents the highest level of absenteeism and labor complaints due to MSDs at the company's medical department. Therefore, among the 21 existent assembly cells, our case study took place at the three assembly cells with the highest level of employees' complaints. These cells present specific characteristics, as shown in Table 5. Cells A and C are the ones that present the heaviest parts assembled in the whole assembly unit, while Cell B is the one with the fastest demand pace, around 20 s per part, which entails the highest frequency of employees' performed tasks within the cell. Moreover, these three cells have been through an extensive amount of lean training and have been sustaining lean practices in a cell level, which carves the scenario of this research.

The tasks performed in these cells are mainly manual operated with driveshaft components assembled. The framework was conducted among 18 cell workers, which are distributed among three different work shifts. The researchers, specialists (ergonomics and lean expertise), and managers performed six meetings to conduct and discuss the ongoing research. The researchers visited the company several times to perform the application of the proposed framework and to record some general data. These data included the age, height, weight, and period of work of each worker. Also, the medical department was contacted to collect workers' physical claims, absenteeism index, and their main medical records (see Table 6).

<Insert Table 5 about here>

TABLE 5. Main Characteristics of Assembly Cells Included in the Case Study

<Insert Table 6 about here>

Table 6 General Data of Participants

4.2. Perceived Workload and Psychophysical Demands

The perceived workload workers, after their working shift, were invited to answer questions on mental, physical, temporal, performance, effort, and frustration aspects. The results shown in Figure 2 present that, for physical profile, effort aspects are the main perceived components of their workload (mostly between Levels 3 and 5). This result is somewhat consistent with senior management expectations. These cells were primarily selected because of the history of workers' physical complaints, in which the usual comments registered by the company's medical department were related to how hard workers had to perform to accomplish production targets in these cells. Further, for psychological profile, results show a low level of workers' capability, which is mostly scored between Levels 1 and 3. Because GHQ questionnaire is a self-administered screening questionnaire, designed for use in consulting settings aimed at detecting individuals with a diagnosable psychiatric disorder, this outcome highlights the psychological limitation of the workers involved with these cells. In addition, the frustration level, which was assessed with NASA-TLX, complements to indicate high levels of irritation and stress that workers feel during the tasks' performance.

For psychophysical demand evaluation, researchers assessed each operation of the cells included in the study. The demand's results are presented in the Table 7. The numbers on the table refer to the inverted 5-point scale of the method, attributed by the specialists after several technical observations, according to the RNUR guidelines. These observations were made during different work shifts, and video records were used to facilitate the process. Note that a few criteria presented a constant demand among operations, such as *Thermal environment*, because all operations are subjected to the same thermal conditions. Similarly, for the psychological demands, criteria *Initiative*, *Thoroughness*, and *Identification* showed a

constant demand among operations, except for the last operation in each cell because it comprises quality inspection activities that significantly differ from the previous operations. In opposition, physical criteria *Heavy objects handling* and *Supply-removal* presented a significant variability with regards to work demand among operations.

<Insert Figure 2 about here>

Figure 2 Physical and psychological profiles of the perceived workload using NASA-TLX and GHQ.

<Insert Table 7 about here>

TABLE 7. Psychophysical Demands of Each Operation

4.3. Gap Analysis

All results for perceived workload and psychophysical demands were compared regarding each cell's operation. The difference value (gaps) between them is shown in Table 8. Each gap value represents the difference between psychophysical demands of each operation (displayed in Table 7) and the average perceived workload profiles for each operation (whose values are consolidated in Figure 2). These values may vary from -4 to 4 and indicate the level of work adaptation to its workers' profile. The lowest values in one criterion (e.g., heavy objects handling/effort) indicate the specific needs of improvement for each cell operation (e.g., Cell A/Operation 4, or A4).

As it can be seen on the results, the gaps of the same operation in each cell tend to be similar. The gap for Criterion 5 (*thoroughness/frustration*) of Cell A/Operation 1 is 2.11 as well as Operation 1 of Cells B and C. This occurs due to its similarities in terms of working conditions and workers' profile. The *heavy objects handling/effort* (Criteria 1) has received higher levels for Operations 3 and 4 in each cell. This result was consistent with experts'

initial expectation given the nature of these assembly tasks, in which the products are much heavier in the final stages of assembly than they are in the beginning of the cell. However, some of the pointed gaps are operation and cell specific, such as the ones for the physical criteria *Supply-removal*, for which only Operations 2 of Cells B and C were identified as critical. In opposition, the criteria *Thermal environment* and *Initiative* should be broadly approached because they present an overall influence in all operations of all cells. Therefore, Table 9 indicates the main improvement actions that need to be addressed according to the identified gaps in order to systemically mitigate psychophysical issues in these cells.

<Insert Table 8 about here>

TABLE 8. Gap Values for Each Operation

<Insert Table 9 about here>

TABLE 9. Gap Analysis

5. CONCLUSION

The main findings of this case study suggest that the gap analysis between psychophysical demands and perceived workload could be a helpful approach to lean production systems. The psychophysical demands results show inconformity with the workload perceived by these cells workers. This result indicates that, despite the fact that several lean practices, such as the standardized work, have already been implemented in these cells, the traditional approach is not sufficient to define workers' tasks, and a complementary method should be used. Further, the traditional approach to lean practices adoption would bring the work demand analysis over several characteristics. The proposed framework confronts that type of analysis with the workers perception, highlighting the gaps between demands and workload in cells undergoing a lean implementation. The complementary method proposed here fulfills

ergonomics gaps that might be neglected during the lean implementation in assembly cells. This fact is especially justified due to the existence of systemic psychophysical demand gaps present in all workstations. Therefore, our method contributes to lean practices implementation because it identifies psychophysical issues and addressing improvement actions.

Despite the contribution of our study, further researches are necessary to improve the comprehension around the subject. In our study, only six criteria (out of several existing criteria in literature) were elected for assessment of psychophysical demands. This was a consequence of the case study that was used to illustrate the proposed method. Therefore, our results applicability in other companies is limited because of this scenario. An approach that is supported by complementary criteria, providing a general overview about the problem, is fundamental for companies' real-life problems.

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TABLE 1. Literature Trend Analysis on Evolution of Lean Thinking and Its Risk Factors and Health Effects

	1980–1990 Awareness	1990–mid-1990s Quality	Mid-1990s–2000 Quality, Cost, and Delivery	2000+ Value System
Literature theme	Dissemination of shop-floor practices	Best-practice movement, benchmarking leading to emulation	Value stream thinking, lean enterprise, collaboration in the supply chain	Capability at system level
Implementation focus	JIT techniques and cost	Cost, training and promotion, TQM, process reengineering	Cost, process based to support flow	Value and cost, tactical to strategic, integrated to supply chain
Key business process	Manufacturing shop-floor only	Manufacturing and materials management	Order fulfilment	Integrated processes such as order fulfillment and new product development
Sectors examined	Automotive—vehicle assembly	Automotive—vehicle and component assembly	Manufacturing in general—often focused on repetitive manufacturing	High- and low-volume manufacturing, extension into services
Lean effects theory development	Lean production brings only negative effects to workers health		Lean production has mixed effects (increased workload but better psychosocial environment)	Controversial results (negative and mixed effects). Effects are depending on the sector and lean practices implemented
Main risk factors and health effects investigated	MSD	MSD and stress	Psychosocial factors and stress	Psychosocial factors and stress

Note: Adapted from Koukoulaki (2014) and Hines et al. (2004).

TABLE 2. Psychological and Physical Workers' Perceived Workload

Criteria		
Physical Perceived Workload Criteria		
Method	Criteria	Description
NASA-TLX	Performance	It represents how successful the worker feels in accomplishing the goals of the task considering lean production characteristics such as standardized work
	Effort	It represents how hard the worker has to work to accomplish his level of performance
Psychological Perceived Workload Criteria		
Method	Criteria	Description
NASA-TLX	Frustration	It represents how insecure, discouraged, irritated, stressed, and annoyed versus secure, gratified, content, relaxed, and complacent did the worker feel during task
GHQ	Psychic stress	It represents evidences of tension, irritation, impatience, fatigue, and overload that make the worker's life a constant, exhausting, and unhappy fight
	Performance suspicion	Expresses the awareness of being able to play or perform daily tasks satisfactorily

TABLE 3. Psychological and Physical Work Demands Criteria

Physical Demand Criteria		
Method	Criteria	Description
RNUR	Heavy objects handling	The compatibility between the height of heavy objects handling during the task and the worker height
	Supply-removal	The compatibility between the dimensional characteristics of feeding and evacuation devices and the normal worker postures
	Thermal environment	The risk of thermal discomfort considering air temperature and the dynamic workload on a workstation
Psychological Demand Criteria		
Method	Criteria	Description
RNUR	Initiative	The possibility of the worker vary its work rhythm without perturbing production
	Thoroughness	The level of worker skills needed to maintain satisfactorily the task
	Identification	Elements of motivation and satisfaction linked to the task of compliance

TABLE 4. Relations between Framework Criteria

	Criteria	Perceived Workload Criteria	Comments
Physical	1 Heavy objects handling	Effort	The height of heavy objects handling should be adapted to anthropometric characteristics of the workers in order to reduce effort
	2 Supply-removal	Performance	The workstation's physical design and/or work organization should be facilitated to improve workers' performance
	3 Thermal environment	Effort	The thermal environment should be controlled avoiding extreme heat or cold temperatures to reduce influence on workers effort
Psychological	4 Initiative	Psychic stress	Task and work organization must allow that workers leave their workstations whenever it is needed so the psychic stress is reduced to a minimum level
	5 Thoroughness	Frustration	The level of worker skills needed should consider psychosocial characteristics of the workers so the level of frustration on the job does not get uninteresting
	6 Identification	Performance suspicion	The tasks and the products should motivate and bring satisfaction to workers so they perform their job without suspicion

Table 5. Main Characteristics of Assembly Cells included in the Case Study

Assembly cell	Employees per Shift	Working Shifts per Day	Parts Demand per Shift	Assembled Parts Average Weight (kg)	Absenteeism Level (%)
A	4	1	840	8.45	8.3
B	3	3	1,260	4.02	9.4
C	3	1	910	8.09	9.8

TABLE 6. General Data of Participants

Data	Mean	Standard Deviation
Age	29.21	6.48
Height (cm)	175	6
Weight (kg)	78.93	12.87
Working time (months)	60.06	65.79
Physical claims	1.79	1.65
Absenteeism (days)	13	10.71
Medical records	Hearing loss, musculoskeletal pain (shoulders, elbows, wrists, hands, knees, hips, low back)	

TABLE 7. Psychophysical Demands of Each Operation

Criteria		Cell A				Cell B			Cell C		
		Op. 1	Op. 2	Op. 3	Op. 4	Op. 1	Op. 2	Op. 3	Op. 1	Op. 2	Op. 3
Physical	1 Heavy objects handling	5	4	1	1	5	3	2	5	3	1
	2 Supply-removal	4	4	4	5	4	3	5	4	3	5
	3 Thermal environment	1	1	1	1	1	1	1	1	1	1
Psychological	4 Initiative	2	2	2	2.5	2	2	2.5	2	2	2.5
	5 Thoroughness	4	4	4	5	4	4	5	4	4	5
	6 Identification	2.5	2.5	2.5	1.5	2.5	2.5	1.5	2.5	2.5	1.5

Note: Inverted values of RNUR, considering that greater is better.

TABLE 8. Gap Values for Each Operation

Criteria		Cell A				Cell B			Cell C		
		Op. 1	Op. 2	Op. 3	Op. 4	Op. 1	Op. 2	Op. 3	Op. 1	Op. 2	Op. 3
Physical	1 Heavy objects handling	1.32	0.32	-2.68	-2.68	1.32	-0.68	-1.68	1.32	-0.68	-2.68
	2 Supply-removal	1.37	1.37	1.37	2.37	1.37	0.37	2.37	1.37	0.37	2.37

Psychological	3 Thermal environment	-2.68	-2.68	-2.68	-2.68	-2.68	-2.68	-2.68	-2.68	-2.68
	4 Initiative	0.05	0.05	0.05	0.55	0.05	0.05	0.55	0.05	0.05
	5 Thoroughness	2.11	2.11	2.11	3.11	2.11	2.11	3.11	2.11	2.11
	6 Identification	0.76	0.76	0.76	-0.24	0.76	0.76	-0.24	0.76	0.76

Note: Headline numbers represent the average values of the six criteria used.

TABLE 9. Gap Analysis

Criteria		Improvement Suggestions
Physical	1 Heavy objects handling	Operations A3, A4, B3, and C3 should be prioritized on this behalf. The work heights on each workstation must be realigned to the workers height (mean 175 cm) and parts weighting until 8.45 kg.
	2 Supply-removal	The workstations B2 and C2 must be redesigned in terms of material feeding and evacuation height, distance, and positioning in order to demand less awkward postures.
	3 Thermal environment	This can be classified as a systemic gap because of the high levels of heat on each workstation and the cells proximity. Improvement actions on this criterion usually require high investments and should not be implemented based only on the results presented here.
Psychological	4 Initiative	There is no specificity of operations on this criterion because the assessed work organization appears to affect all three cells. This systemic gap must be improved through management actions such as hiring more workers that are able to replace turnovers.
	5 Thoroughness	Considering the low cycle time, this is not a great concern but could be improved on operations A1, A2, A3, B1, B2, C1, and C2 because they do not present work elements other than just assembly (such as quality inspection).
	6 Identification	Three quality-related operations are critical on this criterion: A4, B3, and C3. Improvement actions here could follow the same logic of the “Thoroughness” criterion and insert assembly actions into these operations.

Figure 1 – Proposed framework main steps

Figure 2 – Physical and psychological profiles of the perceived workload using NASA-TLX and GHQ

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