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J. W. van Rhijn[a]; M. P. de Looze; G. H. Tuinzaad[b]; L. Groenesteijn[a]; M. D. de Groot[a]; P. Vink[a]
[a] TNO Work and Employment, Department of Ergonomics and Innovation, 2130 AS Hoofddorp, The Netherlands [b] TNO Industrial Technology, Department of Assembly Engineering, 5600 HE Eindhoven, The Netherlands

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Changing from batch to flow assembly in the production of emergency lighting devices

J. W. VAN RHIJN*†, M. P. DE LOOZE†‡, G. H. TUINZAAD§, L. GROENESTEIJN†, M. D. DE GROOT† and P. VINK†

†TNO Work and Employment, Department of Ergonomics and Innovation, PO Box 718, 2130 AS Hoofddorp, The Netherlands
‡Faculty of Human Movements Sciences, Vrije Universiteit, Amsterdam, The Netherlands
§TNO Industrial Technology, Department of Assembly Engineering, PO Box 6235, 5600 HE Eindhoven, The Netherlands

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Current assembly enterprises are under a lot of pressure, as they are faced with increasing volume demands and product variations, needs for shorter delivery times and cost reduction. This pressure is likely to increase the pressure on individual workers. In many small to medium-sized enterprises (SMEs), we observe that traditional assembly concepts are no longer fulfilled. These are challenged to find other concepts to meet today's demands. In a company where emergency lighting devices are assembled in batches (large series of products are assembled step by step), we applied a participatory and integrative approach to set up a mixed flow assembly system including ergonomically designed work stations. In this paper, we describe the approach and the effects which were studied by a within-subject design. We observed an increase of 44% in productivity and a reduction in order lead time of 46%. The time that workers spent to added-value activities increased significantly from 74% to 92%, without any increase in postural and experienced loads. Instead, the workers experienced significantly less overall fatigue at the end of the day in the new situation. The results show the potential benefits of the approach for the many SMEs where products are assembled in batches and faced with the problem of meeting current production demands.

Keywords: Flow assembly; Productivity; Ergonomics

1. Introduction

In the current world, small to medium-sized (assembly) enterprises (SMEs) are under a lot of pressure. To survive worldwide competition, they are forced to produce ever-increasing volumes. Meanwhile, they experience increasing demands for variations in products and shorter delivery times. There is also increasing pressure to

*Corresponding author. Email: g.vrhijn@arbeid.tno.nl

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reduce the cost price while retaining quality. This pressure on companies is likely to increase the pressure on workers.

Most urgent problems for many SMEs in the Netherlands are the logistics to produce higher volumes per unit of time, the lack of space to run the assembly processes, and the retainment of a healthy and motivated work force. It appears that the traditional assembly concepts (particularly, the concept of assembling in batches) which were used by these companies for many years are no longer fulfilled (Tuinzaad *et al.* 2000, van Rhijn *et al.* 2002). Thus, there is a challenge to find other concepts to solve the logistic, spatial and human factor problems.

A change in production concept and its effect on production and workers have been addressed before. In particular, the change from parallel dock assembly towards some type of serial flow assembly (e.g. Fredriksson *et al.* 2001, Neumann *et al.* 2002, de Looze *et al.* 2003) and vice versa (e.g. Johansson *et al.* 1993, Sawamura *et al.* 1996, Engstrom *et al.* 1996, Melin *et al.* 1999) have been studied. Positive effects have been reported for both types of change, in terms of both production output and human factors. Negative effects on workers that have also been reported mainly concern the serial flow concept (Ólafsdóttir and Rafnsson 1998, Fredriksson *et al.* 2001, Neumann *et al.* 2002). General conclusions however, are hard to draw, as usually, along with the concept change, many other changes frequently occur, either intentional (organizational and ergonomic) or unintentional (in production volume, product mix, work force and so on). To the author's knowledge, no reports have been made thus far about the effects on variables regarding the production and the worker, of a change from some type of batch assembly where a series of products is assembled step by step (in clear contrast with one piece flow) towards any other concept.

Recently, we supported an assembly company in the process of changing from batch assembly to another type of concept in their final assembly, and we analysed the effects.

This company (Faber Electronics B.V.) produces emergency lighting devices, which are assembled at large tables in batches of 60 products (figures 1 and 2). This company experienced a steep increase in the market demand, because of two events, an explosion of a fireworks factory and a fire in a pub, which took place in 2000 and 2001 in the Netherlands. This company already had plans to expand their factory because of a presumed lack of space but first decided to critically analyse their traditional assembly concept.

To support the company, we applied our participatory and integrative approach (de Looze *et al.* 2003). Active involvement of company representatives in this approach is crucial, for reasons that have been previously discussed (Noro and Imada 1992, Vink *et al.* 1995, de Looze *et al.* 2001). Another basic feature is that two disciplines are brought together, namely ergonomics and assembly engineering. The approach resulted before in changes from batch assembly to new types of assembly in various other companies (Tuinzaad *et al.* 2000). A solid and quantitative effect evaluation, however, never took place.

This paper describes the process of finding and implementing the new concept as well as the effects of the new concept in terms of productivity, order lead time,

Figure 1. One of the emergency lighting devices produced by the company.

space requirements, and physical and mental loads on the workers. The results are relevant to the other SMEs, where today's production demand cannot be met by their traditional way of stepwise assembling large batches.

2. Methods

2.1 *Assembly of emergency lighting devices*

The main production process of the emergency lighting devices comprises various pre-assembly steps prior to final assembly and expedition. This paper focuses on the final assembly stage, although the project also considered the process as a whole. In the final assembly stage, the electronic unit and other components like the tube luminescent (TL), the reflector, and the battery are assembled and packed. The emergency lighting devices are assembled at large tables in batches of sixty products (figure 2). For each batch, two persons are working at one of the long sides of the table (figure 3). Their work involves fetching the first component, spreading it out across the long table (60-fold), and assembling the component. These activities are repeated for the second component. This pattern continues until the final component

Figure 2. Products are assembled in batches of 60 products.

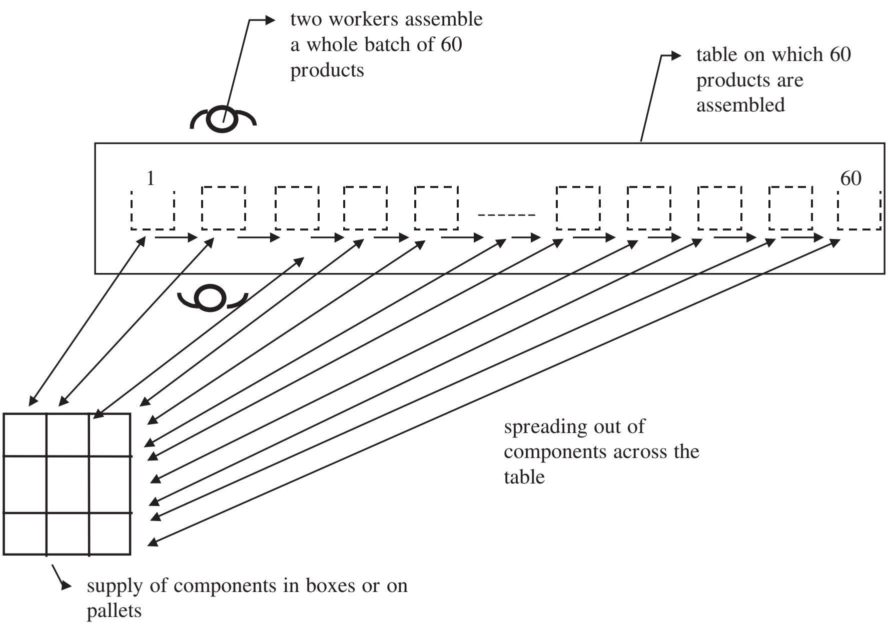

Figure 3. Traditional concept of assembly of emergency lighting devices.

is assembled, and the product is packed. This work pattern requires a considerable amount of walking, especially if larger components are involved.

2.2 *Participatory and integrative approach*

The approach, from start to implementation, includes seven steps. For a formal definition of this approach in more detail, we refer to de Looze *et al*. (2003). A short overview is given below.

The first step comprises the initialization of a multidisciplinary working group within the company. This small working group involves a mix of participants, including assembly operators (2), middle management (1), process engineers (1), planning and logistics, (1) production management (1), and management (1). The working group is supervised by two external specialists: one assembly engineer and one ergonomics engineer. The specialists guide the company through the process and give their expert input.

The second step involves the analysis of the assembly process by setting up a 'Montage Afloop Schema' (MAS) (Tuinzaad *et al*. 2000). The MAS is an assembly process scheme, which is drawn on paper during working group sessions. It visualizes the sequence of the various process steps, which are required to assemble a certain product (figure 4). Process steps that can occur in parallel are visualized in parallel with the main process flow. The scheme also indicates where in the process these steps should finish. Estimates of the time required for each process step are indicated. On the basis of the MAS, the current layout with its various workplaces is drawn. Questions to be solved include: what happens where and how is the transport in between workplaces? Finally, the organization of the work among people is illustrated, e.g. do people make the whole product or only a part?

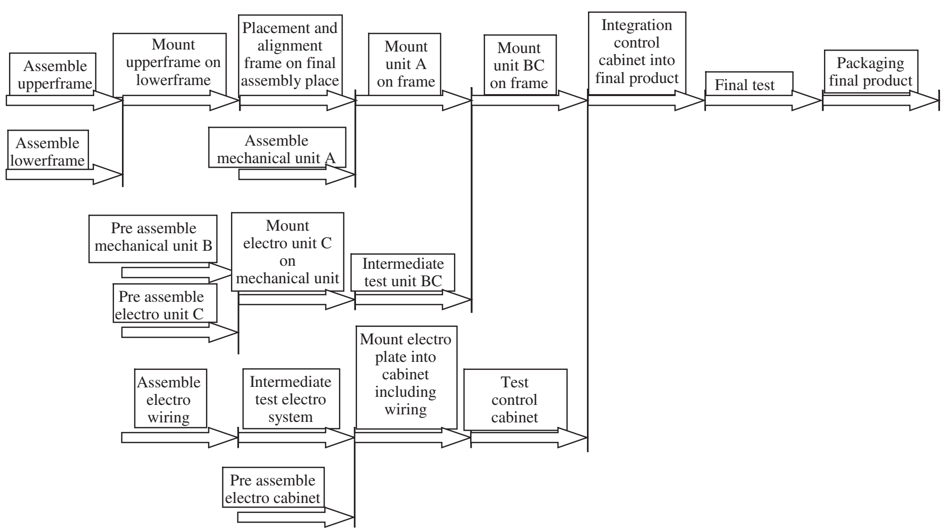

Figure 4. Example of an assembly process scheme (MAS), which visualizes the sequence of the various process steps required to assemble a certain product.

The above forms the starting point for further analysis of failures and improvements in product design, process design, factory layout, and workstation design.

In the third step, the working group makes an inventory of the bottlenecks with regard to the material flow and ergonomics. To add input to the working group sessions, direct observations of the assembly work are made. Interviews with workers also take place, in which we address items like the factory layout, the delivery of components, the availability of tools and equipment, the time needed to walk and search for tools and components, as well as the physical and mental loads in assembly or transport. In addition, the assembly work and manual transport of materials are recorded by video. The video frames are also shown to the whole working group. On the basis of the observations, interviews and the video records, the bottlenecks and possible solutions are discussed in the group. In the current project, the observations took one entire shift; four different workers were observed and interviewed.

In the fourth step, alternative assembly concepts including transportation systems are assessed and compared. Based on total work content and expected production volume and product variability, the required number of workstations is determined. Next, various concepts are discussed in the working group. These concepts are evaluated on the basis of various criteria which concern the flow of materials, the logistics, the balancing of activities, the work/job content per individual, the time to learn (for new employees), and the flexibility to cope with volume and product variances, required space and investments. On the basis of these evaluations, one of the assembly concepts is selected for implementation.

In the fifth step, the selected assembly concept is designed in details: the involvement of people is noted, and the tasks for the workstation and per worker are defined. Workstations are designed on paper, taking into account the location of components and tools, the requirement of space, and the working and picking heights.

In the sixth step, some test workstations are actually built in cooperation with the production workers. In the test workstation, currently existing tools and equipment are used as much as possible. The workstations are interactively designed, evaluated and adapted. The aim is to check the workstation designed on paper: the location of components and tools, the requirement of space, and the working and picking heights.

The assembly line and workstations are actually built and implemented in the seventh step.

In this project, steps 1–6 took 3 months (two sessions of the working group per week), step 7 took 6 months (including the time lost to order and receive the new equipment).

2.3 *Effect evaluation*

Six workers, who were familiarized with the traditional and the new concept (for a period of six months at least), participated in this experiment. Their general experience in assembly work ranged from 1.5 to 12.5 years. The average age of this subject group was 30.7 years (range 21–41 years).

As both assembly concepts, the traditional and the new one, were simultaneously operative, we were able to test the subjects in both conditions and thus, to apply a within-subject design wherein the work condition (traditional vs. new) was the independent variable and the various production and human factors variables were the dependent ones.

In this test, the subjects worked in the traditional and new concept for an entire working day while various subjective and objective measures were captured. The subjects were asked to perform their tasks as they usually do (including task rotation in the new concept, for instance; see next paragraph) and in their normal working pace.

Under both conditions, we measured the productivity in terms of the number of products per person per day. Furthermore, we calculated the order lead time, i.e. the duration of stay of product in the line. The required floor surface was measured, including the workbench, the walking space at the workplace and the material storage space at the workplace. From video recordings under both conditions, we divided the activities into added value (assembling, mounting) and non-added-value (walking, sorting, searching) activities, and we calculated the time of added-value activities as a percentage of the total working time.

With respect to the physical load on the workers, we determined the time of occurrence of risky body segment postures, the occurrence of risky lifting situations and the physical load and fatigue experienced. The posture analysis was based on video recordings, and the risky lifting situations were determined by use of the NIOSH equation (Waters *et al.* 1993). To measure the locally perceived discomfort (LPD) in the various body regions, we used the validated LPD-method (van der Grinten and Smitt 1992), where levels of discomfort were rated on a Borg CR-10 scale, ranging from 0 to 10, where 0 = no discomfort and 10 = extreme discomfort (almost maximum), and the other numbers points were also verbally anchored. In addition, we used a standardized questionnaire to evaluate the old and new situation. This questionnaire addresses the following items: physical load, mental load, worker satisfaction, health risks and fatigue experienced. The validity and reliability of this Dutch questionnaire have been determined by Hildebrandt (2001). Paired *t*-tests or Wilcoxon ranked pairs (in case of application of point scales) were used to determine the significance of differences (at $p = 0.05$) between both situations.

3. Results

3.1 *Assembly process scheme (step 2)*

In the assembly process scheme for the emergency lighting device, all subsequent activities that are required to assemble one device are presented. This scheme was made using the method MAS. The scheme was helpful to indicate the type of added value activities (assembly) and non-added value activities (fetching and spreading out components). By developing the assembly process scheme, all participants acquired the same level of the knowledge, which was not the case beforehand.

3.2 *Bottlenecks (step 3) and new assembly concepts (step 4)*

Table 1 lists the various bottlenecks in material flow and ergonomics. From these, three alternative concepts were defined and compared: parallel, line/flow and a mixed system. These concepts are presented in figure 5.

The first concept shows three parallel, individual workplaces. At each workplace one worker assembles a whole product (concept A). The second concept is an assembly line of three workplaces in series, where workers assemble parts of the final product and the products are handed over (concept B). The third concept (C) is a mixed system: two parallel workstations in which nearly all assembly steps are performed by two operators and a third station where the products are finished and packed. Within the working group, we judged these concepts on various aspects like flow of materials, logistics, balancing of activities, work content per individual, time to learn (for new employees), the flexibility to cope with volume and product variances, required space and investments. In concept A, it was assumed to be advantageous for the worker to make a whole product because of a lower degree of monotony in carrying out the tasks and higher worker satisfaction (despite the higher learning time). In addition, it is flexible in the sense that more or fewer people can be involved, depending on the volume demand. A logistic disadvantage of the concept is that the three workplaces need to be identical, which means that the supply of components should be organized in triplicate. Also, the equipment of workstations (tools, aids) must be organized in triplicate.

The (logistical) advantage of concept B is that components are only supplied at one workplace. However, the work content is smaller, while the flexibility is less: three assembly workers are required to keep the line running.

In the final concept (C), the various advantages of concept A and B were combined. Concept C is characterized by an assembly line with three workstations. At two parallel workstations, nearly all assembly steps are performed by two operators. The near-final products are supplied from both workstations to the third workstation where the products are finished and packed. The content of the work is balanced, such that the workers do not have to wait for others. Small buffers in between the first two workplaces and the final one are established so that workers can work on an individually preferred pace.

Instead of a conveyor belt, which may stress the workers, we chose a roller conveyor for the transport of the products from the first two to the final workplace. This roller conveyor was constructed with a certain deviation from the horizontal, such that products would glide from one workplace to the other.

Within the new concept, rotation of workers across the three workplaces takes place every 2 h. Finally, it was decided that the stock of materials present on the work floor should not exceed the required numbers for one production day.

3.3 *New design details (steps 5 and 6)*

In this new assembly line, the workstation design was improved. All components are placed within reach using small boxes in a tilted position. Within the new concept, a large number of container boxes filled with components had to be placed in each workstation. To reduce reaching distances, the size of the boxes was reduced. Hereto, we needed to come to an agreement with the supplying companies. Also, the

Table 1. Bottlenecks in process flow and ergonomics in the traditional assembly concept.

- High order lead time, i.e. long-lasting stay of products in production (in batches of 60).
- Much walking and handling (up to 25–50%) compared to the total time of assembly.
- Badly arranged location of components: difficult to survey.
- Insufficient space to put the components near the products.
- Production, storage and supply require much space.
- Wave-like flow of materials: accumulation of materials prior to and after final assembly, which yields extra handling.
- No intermediate testing of products: in case of failure of one product, high risk of the same failure in all 60 products.
- Highly repetitive work: the performance of repeated series of 60 similar activities.
- Stressful activities like lifting container boxes involving awkward body postures.
- Twisted body postures in some assembling activities because of the orientation of the product on the table.
- Table height cannot be adjusted to individual anthropometry nor to specific tasks
- Sometimes insufficient space on the table: for specific activities, the product is put on the lap to enable a good view of the various components on the table. Consequently, there is much bending of the upper body.
- Horizontal table surface while an inclined table would better support some of the assembling activities.
- Air tools for activities like screwing hang above the table but are not optimally located and balanced. Therefore, the workers have to generate continuous forces to keep the tool in the right position. Because of this, some workers use a battery-driven screwing tool which results in much arm elevation and wrist flexion due to the pistol grip required.
- Frequent lifting of boxes with many components, weighing up to 11–13 kg, because of batchwise production.
- Extra (non-added value) handling activities which concern the spreading out and the replacement of assemble lower frames by carriers. The assemble lower frames are used in the beginning and at the end of the assembly process, while the carriers (11 kg) are used in between.
- The supply of components to supply location near the table occurs within the assembly zone. No clear separation between supply and assembly areas.
- Overly large stocks of components near assembly work station. Therefore, there are unnecessarily high file of boxes (up to 13 kg) which are well above shoulder level.
- Some components are 10–15 m from the work station. Extra handling.
- Relatively heavy container boxes of 11 kg, 13 kg and 30 kg at locations that are too high (on tiles) and too low (on pallets).

design of some supply boxes was modified for a better supply at the assembly workstation. For instance, the boxes with TLs were re-designed such that they could be filled from above, while lamps could be easily picked out from the side. Within the new concept, the workers refilled the boxes themselves.

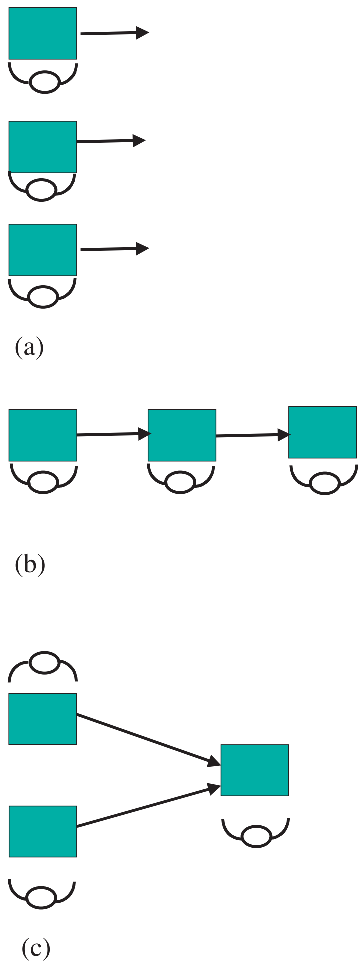

Figure 5. Alternative concepts: (a) three parallel work stations, (b) three work stations in series, and (c) two workstations suppying the third work station (mixed system).

In the first two workstations, where the workers sat, a fixture was placed on which the product could be rotated and tilted. Furthermore, the lighting was improved, the screwing tool was positioned within reach and weightlessly balanced, and new and easily adjustable chairs and tables were implemented. In the final workplace, the worker was standing. Here also, the product could be tilted to facilitate the assembling activities. Finally, to facilitate the assembly, some modifications of the product itself were recommended and applied.

3.4 *Effects*

Table 2 shows the effects of the new system on productivity, order lead time, time of added value activities, and required space. Clearly, favourable effects were observed in all aspects.

Table 2. Productivity, order lead time, time of added-value activities, and space required in the batch and flow assembly concept at Faber.

	Traditional	New	Change (%)
Productivity in number of products per person per day	93.3	134.7	+44
Order lead time (min)	155	72	−46
Time of added-value activities (percentage of total working time)	74	92	+18
Required work space (m^2)	80.5	45	−44

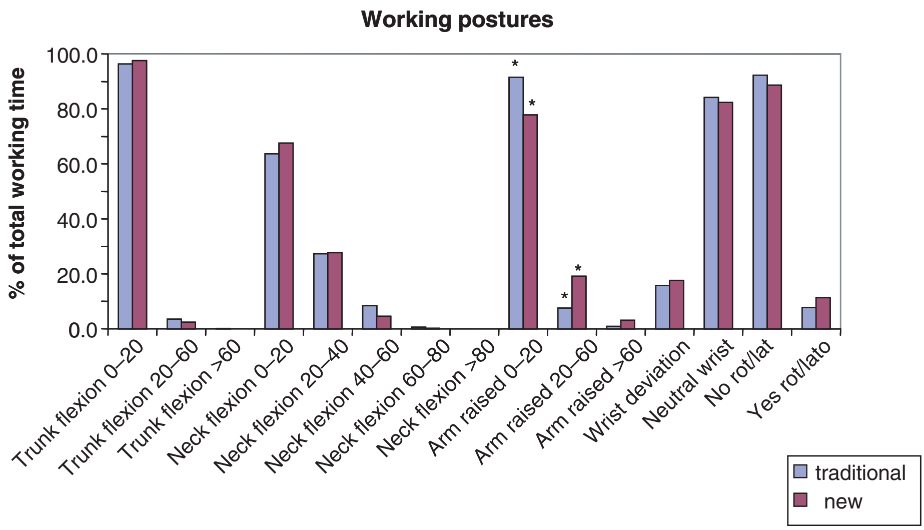

Figure 6. Categorized working postures in the traditional and new situation. *Significant difference at $p = 0.05$; p-value for arm raised $0–20^\circ = 0.006$, and p-value for arm raised $20–60^\circ = 0.001$.

The time of added value activities significantly increased from 74 to 92% (t-test, $p = 0.001$). The other parameters in the table were not determined on individual levels but deduced from general output rates, number of subjects in the line and the required area, and thus could not be statistically tested. Nonetheless, the effects on productivity, order lead time and required workspace are clear (all exceeding 40%), indicating a considerable improvement.

Figure 6 shows the working postures in percentages of total working time. There were no large differences in scored working postures, except for raising arms: in the new situation, we observed slightly more elevated arms within 20–60°.

The NOISH equations for lifting boxes (9.16 kg per box) in the old and new situation showed an improved and safe way of lifting in the new situation. In the traditional situation, the lifting situation was unacceptable due to the low placement (the vertical factor) of the pallets on the floor (30 cm) and the reaching (horizontal factor) before placing. In the new situation, the boxes were placed on

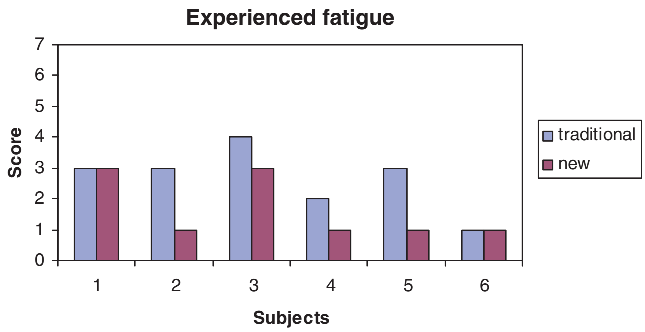

Figure 7. Experienced fatigue in the traditional and new situation scored on a seven-point scale (ranging from 1, (hardly) no fatigue to 7, very much fatigue). The Wilcoxon ranked pairs test was applied, which resulted in a significant finding of lower fatigue in the new situation ($p = 0.038$).

a pallet at an adjustable height (70–80 cm) on a lifting table, and the distance for reaching was not as far.

No differences were found for Locally Perceived Discomfort in different body areas. Workers did experience less overall fatigue in the new situation compared with the traditional situation ($p = 0.038$, Wilcoxon paired rank test) (figure 7). There were no differences in physical load and mental load experienced. Five out of six subjects felt more satisfied in the new working concept. They considered the increased productivity, the improved workstation design and the reduction of lifting tasks to be the reason.

4. Discussion

In the current project, a traditional assembly concept where workers make batches of products from start to end was replaced by a flow concept where workers work on only one product at a time. Hereto, a mixed system of two parallel workstations and a third workstation in line was implemented. The rationale behind the change was the increase in the market volume demand in combination with a lack of space.

This change in combination with some ergonomic workplace modifications resulted in some clear effects. The beneficial effects on production-related measures are beyond dispute. There appeared to be no need for the company to invest in factory expansion. On the same factory area, it appeared to be possible to produce about twice as much when applying the new assembly concept. In addition, we observed a significant reduction in order lead time (46%) and a significant gain with respect to productivity (44%). This gain in productivity is partly based on an increase in the percentage of time that is spent on added-value activities.

This shift towards more added-value assembly work did not lead to a clear increase in the physical or mental loads on the workers. Instead, we observed a decrease in the occurrence of stressful lifting activities and a decreased level of overall fatigue at the end of the day. In the other human-factors variables (local perceived discomfort, experienced physical load, experienced mental load, occurrence of stressful postures in most body segments), we observed no differences between the old and new situation.

One exception concerns the arm posture: a slightly more frequent 'moderate' arm elevation is observed in the new situation. The increased arm elevations can be explained by the fact that part of the time, the workers are seated, which requires more arm elevation when reaching for components from shelves. This disadvantage is now eliminated by modifying the way the components are delivered.

One further point to be discussed concerns the increased time percentage of direct work. Some argue that such development (also addressed as work intensification) may well increase the risk for musculosleletal injury (Winkel *et al.* 2002). Indeed, elevated medically certified sick leave rates have been associated with such work intensification (Vahtera *et al.* 1997). Also, monotonous work in the production industry has been associated with more health problems in the upper extremities and elevated sick-leave rates (Parenmark *et al.* 1993, Johansson and Nonås 1994, Ólafsdóttir and Rafnsson 1998). The theory behind this is that the long periods of time of monotonous assembling activities without interruption of other kinds of (indirect) activity give body structures insufficient opportunities to recover during the day (Winkel *et al.* 2002). At higher percentages of direct work, the need for some kind of variation interrupting the assembly work now and then thus increases. We manage to implement such a variation in several ways.

First, in the new situation, we force the workers to interrupt their assembly work by forcing them to stand up (by using small storage bins) and fetch components at rather fixed intervals of time. Thereby, frequent interruption of the work is guaranteed to some extent, while the total length of time of indirect work is considerably reduced.

Second, some more variation is introduced within the periods of assembly. In the traditional batchwise production, the same action is performed again and again, with 30 different products, prior to proceeding with a new assembly action. By making one product at a time with the new concept, the variation of assembly activities is increased. As the type of these activities is rather diverse, we consider this as a favourable feature. Workers themselves also considered this change as a positive development.

Finally, alternation of sitting and standing is introduced in the new situation, whereas standing was the only way to assemble in the former situation.

In this project, we were fortunate to have the two working conditions, the traditional and the new one, operating simultaneously. This gave us the opportunity to perform the test within a short period of time. Thereby, the confounding effect of unwanted variations (in work force, production output demand, product type, etc.) could be minimized. Moreover, we were able to apply a within-subject design, where subjects were tested under both conditions in random order to exclude any sequence effects. Because of this, the number of subjects that was required was limited. Nevertheless, we consider the number of subjects that we could have in this company as rather low (although the numbers in other studies on ergonomic effects are quite similar or even lower; Kadefors *et al.* 1996, Neumann *et al.* 2002). Despite the low number of subjects, however, we were able to observe a significant effect on the arm elevation and on the level of experienced fatigue. As we did not see any negative trend with respect to the other measured human-factors variables, we concluded that there were no adverse effects on the workers. Additionally, the effects on productivity, order lead time, and time percentage of added work were so clear and sizeable that a higher number of subjects would not have changed this figure.

The results obtained in the present study are well in line with our experiences with previous applications using the same approach in other companies (e.g. producers of mowing machines, car-roof systems, food equipment, office furniture, and magnetic stop valves), where estimated gains in productivity of about 15–20% and order lead times of 20–25% without any increase in physical load parameters were not uncommon (Tuinzaad *et al*. 2000).

Many Dutch SMEs have a traditional way of assembling in batches (similar to that studied here), by which volume and other present-day demands cannot be achieved. For these SMEs, similar results can be achieved using the same participatory and integrative approach. Differences across companies may exist, however, in the concept to be implemented, since the optimal concept depends on many factors, e.g. type of product (size, weight, work content), production volumes, flexibility needs, level of automation, and the availability and type of workers. In the present project, the optimal concept is selected on the basis of an evaluation of criteria, which takes place in a group process, in which experiences and expectations of the people involved have a large influence. The availability of more objective data might be helpful in this respect. Future research efforts should therefore focus on generating relationships between the various factors of influence and their effects (on production and worker) across various assembly concepts.

References

de Looze, M.P., Urlings, I.J.M., Vink, P., van Rhijn, G., Miedema, M., Bronkhorst, R.E. and van der Grinten, M.P., Towards succesful physical stress reducing products. An evaluation of seven cases. *Appl. Ergon*., 2001, **32**, 525–534.

de Looze, M.P., van Rhijn, J.W., Reijneveld, K., van Deursen, J. and Tuinzaad G., A participatory and integrative approach to improve productivity and ergonomics in assembly. *Prod. Plan. Control*., 2003, **14**, 174–181.

Engstrom T., Jonsson, D. and Johansson, B., Alternatives to line assembly: some Swedish examples. *Int. J. Ind. Ergon*., 1996, **17**, 235–245.

Fredriksson, K., Bildt, C., Hagg, G. and Kilbom, A., The impact on musculoskeletal disorders of changing physical and psychosocial work environment conditions in the automobile industry. *Int. J. Ind. Ergon*., 2001, **28**, 31–45.

Hildebrandt, V.H., Prevention of musculoskeletal disorders. Setting Priorities using the standardized Dutch musculoskeletal questionnaire. PhD thesis, Free University, Amsterdam, 2001.

Johansson, J.Å., Kadefors, R., Rubenowitz, S., Klingenstierna, U., Lindstrom, I., Engstrom, T. and Johansson, M., Musculoskeletal symptoms, ergonmioc aspects amd psychosocial factors in two different truck assembly concepts. *Int. J. Ind. Ergon*., 1993, **12**, 35–48.

Johansson, J.Å. and Nonås, K., Psychosocial and physical working conditions ans associated musculoskeletal symptoms among operators in five plants using arc welding in robot stations. *Int. J. Hum. Fac. Manuf*., 1994, **4**(2), 191–204.

Kadefors, R., Engstrom, T., Petzall, J. and Sundstrom, L., Ergonomics in parallellized car assembly: a case study with refernce also to productivity aspects. *Appl. Ergon*., 1996, **27**, 101–110.

Melin, B., Lundberg, U., Soderlund, J. and Granqvist, M., Psychological and Physiological stress reactions of male and female assembly workers: a comparison between two different forms of work organisation. *J. Organ. Behav.*, 1999, **20**, 47–61.

Neumann, W.P., Kihlberg, S., Medbo, P., Mathiassen, S.E. and Winkel, J., A case study evaluating the ergonomic and productivity impacts of partial automationstrategies in the electronics industries. *Int. J. Prod. Res.*, 2002, **40**, 4059–4075.

Noro, K. and Imada, A., *Participatory Ergonomics*, 1992 (Taylor & Francis: London).

Ólafsdóttir, H. and Rafnsson, V., Increase in musculoskeletal symptoms of upper limbs among women after introduction of the flow-line in fish-fillet plants. *Int. J. Ind. Ergon.*, 1998, **21**, 69–77.

Parenmark, G., Malmkvist, A.K. and Örtengren, R., Ergonomic moves in an engineering industry: Effects on sick leave frequency, labor turnover and productivity. *Int. J. Ind. Ergon.*, 1993, **11**, 291–300.

Sawamura, H., Lean manufacturing and productivity improvement activity at NEC., In *Manufacturing Agility and Hybrid Automation—I*, edited by R.J. Koubek and W. Karwowski, 1996 (IEA Press: Louisville, KY).

Tuinzaad, G.H., van Rhijn, J.W., van Deursen, J. and Koningsveld, E.A.P., *Efficient Flow and Human Centred Assembly: The Success of an Interactive Approach*, 2000 (TNO Industrial Technology/TNO Work and Employment: Eindhoven/Hoofddorp).

Vahtera, J., Kivimaki, M. and Pentii, J., Effect of organisational downsizing on health of employees. *The Lancet*, 1997, **350**, 1124–1128.

van der Grinten, M.P. and Smitt, P., Development of a practical method for measuring body part discomfort, In *Advances in Industrial Ergonomics and Safety IV*, edited by S. Kumar, pp. 311–318, 1992 (Taylor & Francis: Philadelphia, PA).

van Rhijn, J.W., de Looze, M.P., Groenesteijn, L., de Groot, M.D., Vink, P. and Tuinzaad, G.H., Efficient flow and human centred assembly. The success of an interactive approach, in *Humans in a Complex Environment, Proceedings of the 34th Congress of NES*, pp. 805–810, 2002 (Linkopings University: Sweden).

Vink, P., Peeters, M., Gründemann, R.W.M., Smulders, P.G.W., Kompier, M.A.J. and Dul, J., A participatory ergonomics approach to reduce mental and physical workload. *Int. J. Ind. Ergon.*, 1995, **15**, 389–396.

Waters, T.R., Putz-Anderson, V., Garg, A. and Fine, L.J., Revised NIOSH-equation for the design and evaluation of manual lifting tasks. *Ergonomics*, 1993, **36**, 749–776.

Winkel, J., Forsman, M., Kazmierczak, K., Kjellberg, A., Mathiassen, S.E., Neumann, P.W. and Wells, R.P., Ergonomic intervention for occuspational musculoskeletal health 7in manufacturing industry—trends, tools and processes, in *Humans in a Complex Environment, Proceedings of the 34th Congress of NES*, pp. 833–835, 2002 (Linkopings University: Sweden).