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Differences between worker pairs in manual assembly: a case study

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Abstract

Working in pairs is common and often necessary to carry out industrial manual assembly tasks. This paper studies differences in performance that can occur between pairs of workers. Within a case assembly product, activity analysis for each worker in a total of ten pairs and up to four repetitions (learning) is conducted on the basis of video evidence. The results show significant variation in assembly time between the pairs. Repetitions reduce the relative variation, while the ranking of the pairs remains mostly unchanged. In general, the time used for installing parts explain most of the variation between the pairs.

Keywords: manual assembly, worker pairs, learning, variation

1. Introduction

In the mechanical engineering industry, working in pairs is typical and often necessary to carry out manual assembly tasks. Pair partners can provide valuable help for each other with both physically [1,2] and cognitively [3] challenging tasks. How well a pair performs depends on the task demands, resources, and process [4]. Resources include knowledge, skills, tools, etc., and how the relevant resources, in terms of task demands, are distributed among the workers. The process then consists of the actual steps taken by a pair of workers to complete the task. Thus, there are several factors affecting pair working and the performance may vary significantly between different pairs. Despite this fact, there are few studies reporting the differences between pairs in manual assembly tasks. In one related study [5], the task differs significantly from tasks in the traditional mechanical engineering industry. There are studies on differences between individuals (e.g. [6,7,8]) and detailed reasons for these [9] in industrial tasks but when it comes

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to pairs, evidence is scarce. Thus, there is a need for detailed studies of the performance of pairs of workers in manual assembly tasks which are similar to those in real-life industry.

This paper responds to this research gap by examining in more detail the ways in which, and the extents to which, the differences between pairs were caused in a previous laboratory study [10,11] by the present authors. This previous study examined the effects of group size and learning on manual assembly performance. The main results showed that, with a new product and novice workers, assembly time decreases (i.e. learning occurs) rapidly through repetition and that productivity per worker decreases as a function of increasing group size (i.e. the number of workers per product). Among the group sizes that were studied (one to four workers per group), pairs of workers showed the greatest variation in performance. Therefore, the present paper focuses on assembly work performed by pairs of workers, and ultimately aims to deepen the understanding of the variation in performance that can occur between them. Considering such variation and the related effective factors gives insights for industrial managers when making decisions on worker assignments and working in pairs on assembly tasks.

The rest of this paper is organized as follows. Section 2 reviews the related literature. Section 3 briefly presents the materials and methods used in this case study. Section 4 presents and discusses the results from the case study. Section 5 concludes the paper and suggests some aspects that merit further research.

2. Literature review

Differences in performance between workers in industrial tasks can be significant. Hunter et al. [6] reviewed a large number of previous studies and determined a CV of 0.2 for productivity among blue-collar workers. An example in [7] shows similar results for automotive assembly work: in a group of six workers, the best one typically performed twice as fast as the worst one. In an experimental study [12] building blocks were assembled with work (motion) elements in order to mimic a real industrial assembly task. The results of the experiments demonstrated a significant heterogeneity among individuals in terms of both mean and variation in assembly time. Rohmert and Schlaich [9] carried out laboratory experiments with a simple task which consisted of grasping washers in a storage box and assembling them onto plugs. The results from a training period lasting several weeks showed that the differences between the four participants were only related to the motion elements *grasp* and *assemble*. The elements *reach* and *move* showed non-significant differences. In general, the differences between the individuals remained unchanged during the training. Interestingly, repetition did not cause any apparent changes in the CV with different elements. Through the training period, an approximate average CV of 0.3 was measured for *assemble*, a CV of 0.18 for both *grasp* and *move*, and a CV of 0.08 for *reach*. The study concludes that rather than training, methods engineering would tackle problems with the *grasp* and *assemble* motion elements. Problems with these motions are also reported in [13].

When multiple workers join together to work on a task, the assembly process and its predictability become more complicated. According to [4], the levels of potential and actual productivity of a group performing a shared task vary as a function of task demands, resources, and group process. Non-optimality in group organization and workers' efforts to create group output cause process losses and the actual productivity falls below the potential. As a pair, two individuals can combine their efforts in an additive or interactive manner [14]. When an additive approach is taken, the effects of the individuals on the pair are independent (e.g. [15]). In interaction, the effects of individuals are, to some extent, interdependent.

Worker interaction is a key element in the success of working in a group. According to the review in [16], interaction can generate new ideas, solutions, or efforts. The review also suggests individual capacity to learn and cognitive stimulation as underlying factors affecting the group process. Many studies characterize high-performing groups that involve a large amount of interaction among the workers. In such groups, workers have an awareness of task status, conditions, and roles [7], are willing to assist each other [17], and provide their knowledge and experience for the benefit of the collective output [18].

Juran and Schruben [5] studied the performance of worker pairs in a serial work-sharing production cell. The tasks consisted of reading, checking, and entering information on a computer keyboard. A total of 48 randomly formed pairs participated in the laboratory experiments. The results showed a mean productivity of 28.25 orders per hour (CV = 0.25). In the study, several simulation models were constructed in order to find out how well the results generated with them fit the laboratory data. In the best model (mean 28.77, CV = 0.25) differences in performance between the pairs of workers were regressed against the personality and demographic attributes of the workers (the attributes for each worker in each pair were generated randomly). The results showed how more detailed information in the model makes more accurate predictions of the behaviour of a real system possible. Another model in the study also showed that when the personal attributes of a particular pair of workers are known, much more accurate estimates of performance can be made. Previous research in [19] found that differences between individual workers explain 80% of the variation in the productivity of serial work-sharing teams.

As individual differences in work performance can be very large, one should pay attention to the selection of workers. This makes possible significant savings in training time and cost [13] and large benefits in productivity [6]. The selection of the most capable workers can utilize different dexterity tests. In such tests, the times of different motion elements can easily be recorded and the capability of a job applicant to learn these elements can be assessed (e.g. [13]). The selection of the most suitable and effective pairs of workers has also received some attention. As stated in [15], “it may be that some or even all subjects will work more effectively with some individuals than with others”.

In pair working, there are several underlying factors affecting the output of a pair. The present literature review suggests that the attributes of individuals have significant effects on the output of pairs. Differences between individuals, and their causes, as well as the selection of individuals for tasks, have, understandably, received attention. Studies also suggest the interactive effects of individuals in working in pairs, which emphasizes the selection of the most suitable pairs of workers. The literature review showed that there is a lack of detailed studies on differences in performance between pairs of workers in manual assembly tasks that are similar to those tasks in real-life industry. These studies should focus on the extents to which, and the ways in which, differences in performance between pairs occur. This includes considering the different activities of pair partners, comprising work motion elements and losses, and how pairs progress with these activities through repetition.

3. Materials and methods

This paper studies differences in performance between pairs of workers in a case assembly task. The research is based on the previous experimental study by the present authors [10,11]. The assembly cell layout and the case product, together with a parts list are presented in Appendix A. The product consists of a structure and components similar to industrial assembly products. The case product was designed in a way that enables close interaction between workers. The participants were undergraduate students with no prior experience of the product in question. Pairs of workers were selected randomly, and each pair performed the assembly either three or four times. In this study, the performance of each worker in a total of ten different pairs is analyzed on the basis of video evidence using the AviX software. In the analysis, different types of activities were specified, as shown in Table 1.

Table 1. Different types of activities

Activity	Explanation
Value-adding, *VA*	installing of parts
Required, *REQ*	necessary picking and handling of parts, small parts and tools; necessary moving in the assembly cell
Instructions, *INSTR*	looking at (reading) the assembly drawing
Losses, *LOSS*	loss types: wrong tool, faulty installing, dropping equipment, co-worker-related, unexpected event, idleness, and other losses (see [11] for more detailed explanations)

4. Results and discussion

Table 2 shows the descriptive statistics of different activities. First, for each repetition (*Rep*), the number of pairs (*N*) is shown. Then, the statistics for the value-adding (*VA*), required (*REQ*), instruction (*INSTR*), loss (*LOSS*), and total assembly time are presented. These statistics include the mean value (mean), standard deviation of times between pairs (SD) and coefficient of variation (CV), median value (median), and minimum (min) and maximum (max) values, as well as the first (25%) and third (75%) quartiles.

Fig. 1(a) presents the assembly times of each pair (marked as Pair#) in different repetitions. Fig. 1(b) visualizes the descriptive statistics of different activities in a boxplot diagram. In the diagram, with each activity and repetition, the central rectangle spans the first quartile to the third quartile. The line segment inside the rectangle shows the median and the "whiskers" below and above the rectangle show the minimum and maximum. An outlier, i.e. a value that is an abnormal distance from other values, is shown as a marker with a label indicating the pair of workers the value is related to. Point markers indicate a mild outlier, whereas star markers indicate an extreme outlier.

Table 2. Descriptive statistics for different activities.

	VA					REQ					INSTR					LOSS					Total assembly time				
Rep	*1*	*2*	*3*	*4*	*Tot.*	*1*	*2*	*3*	*4*	*Tot.*	*1*	*2*	*3*	*4*	*Tot.*	*1*	*2*	*3*	*4*	*Tot.*	*1*	*2*	*3*	*4*	*Tot.*
N	10	10	10	7	37	10	10	10	7	37	10	10	10	7	37	10	10	10	7	37	10	10	10	7	37
Mean	8.65	6.97	6.91	6.36	7.29	4.74	3.98	3.59	3.19	3.93	5.64	1.37	0.54	0.65	2.16	6.12	1.99	0.93	0.73	2.58	25.14	14.30	11.96	10.63	15.90
SD	4.46	2.53	2.02	1.24	2.93	0.73	0.60	0.69	0.57	0.85	1.50	0.91	0.64	0.47	2.37	3.07	1.17	0.31	0.46	2.79	8.61	4.77	3.35	2.60	7.89
CV	0.52	0.36	0.29	0.20	0.40	0.15	0.15	0.19	0.18	0.22	0.27	0.66	1.19	0.73	1.10	0.50	0.59	0.33	0.63	1.08	0.34	0.33	0.28	0.24	0.50
Median	6.70	6.55	6.53	6.14	6.41	4.50	4.00	3.65	2.93	4.08	6.01	1.25	0.45	0.38	1.04	6.10	2.24	0.97	0.51	1.26	23.61	14.76	11.60	9.86	14.66
Min	5.98	4.58	4.97	4.85	4.58	3.56	3.00	2.45	2.49	2.45	3.41	0.31	0.06	0.07	0.06	1.93	0.36	0.40	0.14	0.14	15.24	8.45	7.96	7.49	7.49
Max	20.74	13.13	10.66	8.57	20.74	5.90	5.08	4.39	4.09	5.90	7.80	3.41	2.23	1.40	7.80	13.22	3.57	1.45	1.44	13.22	47.37	24.40	18.42	15.12	47.37
25%	6.30	5.03	5.17	5.62	5.65	4.26	3.44	3.03	2.84	3.31	4.38	0.62	0.10	0.37	0.40	4.31	0.71	0.74	0.42	0.78	20.63	9.73	9.28	9.07	9.72
75%	9.34	7.80	8.12	7.43	8.05	5.35	4.38	4.27	3.76	4.38	6.76	1.78	0.65	0.98	3.45	6.95	2.89	1.07	1.14	3.53	27.27	16.72	14.27	13.10	20.18

a

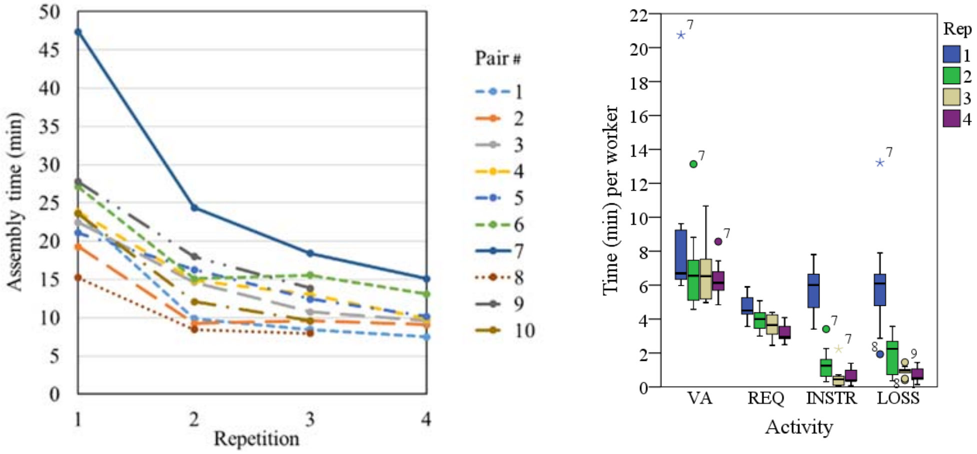


Fig. 1. (a) Assembly times of pairs in different repetitions; (b) boxplot diagram from descriptive statistics.

As Table 2 shows, as the number of repetitions increases, the relative variation (CV) in the total assembly time between the pairs decreases (0.34 to 0.24). The assembly time of the worst-performing pair decreased from about triple to double that of the best-performing pair. Thus, there is a vast difference in performance between the best- and the worst-performing pairs. According to Fig. 1(a), Pair #8 performed best in the first three repetitions, and Pair #1 was the best in the fourth repetition. In each repetition, Pair #7 performed worst. Fig. 1(b) also refers to this as markers indicating the poor performance of that pair in different activities. In general, as Fig. 1(a) shows, the rankings of the pairs remain relatively unchanged through the repetitions. Thus, within the given repetitions, there are permanent differences in performance between the particular pairs. Such evidence has been shown earlier for individuals (e.g. [9]).

According to Table 2, in each repetition, the share of *VA* time of the total assembly time is the greatest, and except with Rep 1, the share of *REQ* time is the second greatest. With Rep 1, the shares of *INSTR* and *LOSS* times are significant. For inexperienced workers, learning about new products uses a lot of resources in familiarizing themselves with the assembly instructions. Inexperience also causes a large number of loss activities, which typically appear as observing and examining parts and their assembly locations [11]. The *LOSS* times between the groups vary significantly in Rep 1 (CV = 0.5). In general, *INSTR* and *LOSS* times can be reduced by paying attention to the clarity and precision of the instructions, as well as to the identification of assembly parts and locations [11]. As *VA* time explains most of the total assembly time and the variation in that between the pairs (see SDs of *VA* times in Table 2), the *VA* times of different assembly parts are studied next. The factors affecting *REQ* times are studied after that.

4.1. VA times of assembly parts

As defined above, *VA* time means time used for installing parts. Table 3 shows the descriptive statistics of part installation times (see the parts list in Appendix A). Fig. 3 visualizes the descriptive statistics in a boxplot diagram. It is noteworthy that Table 3 and Fig. 2 present the total minutes used to install parts.

Table 3. Descriptive statistics of part installation times

	P1					M1					P2					M2				
Rep	*1*	*2*	*3*	*4*	*Tot.*	*1*	*2*	*3*	*4*	*Tot.*	*1*	*2*	*3*	*4*	*Tot.*	*1*	*2*	*3*	*4*	*Tot.*
N	10	10	10	7	37	10	10	10	7	37	10	10	10	7	37	10	10	10	7	37
Mean	1.34	0.94	0.97	0.95	1.06	0.84	0.63	0.56	0.67	0.67	1.58	2.11	2.05	1.17	1.77	0.95	0.70	0.71	0.85	0.80
SD	0.80	0.34	0.30	0.33	0.51	0.34	0.23	0.17	0.35	0.28	0.70	1.44	2.30	0.24	1.45	0.25	0.11	0.22	0.35	0.25
CV	0.59	0.36	0.31	0.35	0.48	0.41	0.36	0.30	0.52	0.42	0.45	0.68	1.12	0.20	0.82	0.26	0.16	0.31	0.41	0.31
Median	1.18	0.92	0.90	0.84	0.93	0.71	0.55	0.54	0.57	0.57	1.37	1.63	1.33	1.19	1.37	0.97	0.70	0.64	0.77	0.76
Min	0.63	0.50	0.57	0.61	0.50	0.50	0.40	0.39	0.30	0.30	1.03	0.55	0.77	0.77	0.55	0.63	0.49	0.42	0.49	0.42
Max	3.24	1.51	1.46	1.57	3.24	1.49	1.16	1.01	1.29	1.49	3.41	4.57	8.51	1.47	8.51	1.28	0.82	1.17	1.31	1.31
25%	0.69	0.64	0.77	0.70	0.70	0.58	0.46	0.47	0.43	0.49	1.14	0.87	1.05	1.01	1.08	0.67	0.60	0.56	0.54	0.61
75%	1.72	1.25	1.18	1.23	1.25	1.09	0.75	0.56	0.95	0.81	1.69	3.16	1.88	1.37	1.75	1.20	0.81	0.83	1.31	0.94

	M3					P3					H1				
Rep	*1*	*2*	*3*	*4*	*Tot.*	*1*	*2*	*3*	*4*	*Tot.*	*1*	*2*	*3*	*4*	*Tot.*
N	10	10	10	7	37	10	10	10	7	37	10	10	10	7	37
Mean	1.82	1.08	0.95	0.83	1.20	1.24	0.97	1.17	1.10	1.12	0.79	0.64	0.60	0.87	0.71
SD	1.68	0.38	0.29	0.20	0.96	0.86	0.46	0.98	0.97	0.80	0.42	0.16	0.18	0.21	0.28
CV	0.92	0.35	0.30	0.25	0.80	0.70	0.47	0.84	0.88	0.72	0.53	0.25	0.29	0.24	0.39
Median	1.34	1.04	0.93	0.83	1.04	1.01	0.85	0.82	0.69	0.89	0.68	0.59	0.56	0.92	0.64
Min	0.91	0.66	0.60	0.59	0.59	0.65	0.51	0.44	0.43	0.43	0.46	0.48	0.42	0.59	0.42
Max	6.53	1.87	1.45	1.11	6.53	3.62	2.00	3.46	3.10	3.62	1.93	1.01	0.93	1.14	1.93
25%	1.15	0.76	0.68	0.63	0.76	0.83	0.64	0.62	0.45	0.65	0.59	0.53	0.44	0.63	0.53
75%	1.56	1.33	1.18	1.04	1.29	1.22	1.24	1.28	1.59	1.17	0.81	0.73	0.75	1.02	0.80

	PL					P4					H2					V				
Rep	*1*	*2*	*3*	*4*	*Tot.*	*1*	*2*	*3*	*4*	*Tot.*	*1*	*2*	*3*	*4*	*Tot.*	*1*	*2*	*3*	*4*	*Tot.*
N	10	10	10	7	37	10	10	10	7	37	10	10	10	7	37	9	9	9	7	34
Mean	1.72	1.33	1.24	1.32	1.41	1.10	0.82	0.75	0.75	0.87	2.09	1.75	1.81	1.59	1.83	1.07	0.63	0.77	0.87	0.83
SD	1.24	0.67	0.38	0.25	0.76	0.92	0.53	0.26	0.41	0.59	0.86	0.56	0.70	0.12	0.65	1.14	0.30	0.55	0.55	0.70
CV	0.72	0.51	0.31	0.19	0.54	0.83	0.64	0.35	0.55	0.68	0.41	0.32	0.39	0.07	0.36	1.07	0.48	0.72	0.63	0.84
Median	1.27	1.21	1.11	1.24	1.20	0.72	0.65	0.83	0.63	0.67	1.70	1.60	1.54	1.56	1.58	0.60	0.59	0.61	0.65	0.61
Min	0.79	0.82	0.74	1.09	0.74	0.47	0.41	0.39	0.35	0.35	1.48	1.20	1.17	1.43	1.17	0.44	0.39	0.27	0.42	0.27
Max	4.87	3.14	1.87	1.71	4.87	3.43	2.22	1.04	1.52	3.43	4.06	3.08	3.42	1.80	4.06	3.97	1.36	2.20	2.04	3.97
25%	0.92	0.93	0.96	1.10	0.97	0.58	0.55	0.46	0.43	0.55	1.54	1.39	1.30	1.50	1.46	0.47	0.41	0.57	0.50	0.49
75%	1.95	1.40	1.55	1.63	1.49	1.30	0.84	0.98	1.10	1.00	2.54	1.95	2.20	1.66	1.82	1.22	0.71	0.74	1.00	0.79

	H3					P5					Total				
Rep	*1*	*2*	*3*	*4*	*Tot.*	*1*	*2*	*3*	*4*	*Tot.*	*1*	*2*	*3*	*4*	*Tot.*
N	9	9	9	7	34	10	10	10	7	37	128	128	128	91	475
Mean	0.34	0.19	0.17	0.15	0.22	2.49	2.15	2.12	1.59	2.13	1.35	1.08	1.08	0.98	1.13
SD	0.22	0.13	0.04	0.03	0.15	1.50	1.81	1.33	0.50	1.40	1.07	0.91	0.99	0.54	0.93
CV	0.66	0.68	0.24	0.20	0.69	0.60	0.84	0.63	0.32	0.66	0.79	0.84	0.93	0.55	0.82
Median	0.22	0.16	0.15	0.15	0.17	1.82	1.57	1.80	1.47	1.71	1.08	0.81	0.82	0.94	0.92
Min	0.14	0.11	0.12	0.10	0.10	1.15	1.01	1.00	1.09	1.00	0.14	0.11	0.12	0.10	0.10
Max	0.81	0.54	0.24	0.19	0.81	5.84	7.12	5.16	2.57	7.12	6.53	7.12	8.51	3.10	8.51
25%	0.18	0.12	0.13	0.13	0.14	1.58	1.25	1.13	1.11	1.23	0.65	0.57	0.57	0.60	0.60
75%	0.48	0.20	0.19	0.17	0.22	3.63	2.18	2.75	1.77	2.28	1.55	1.35	1.22	1.31	1.39

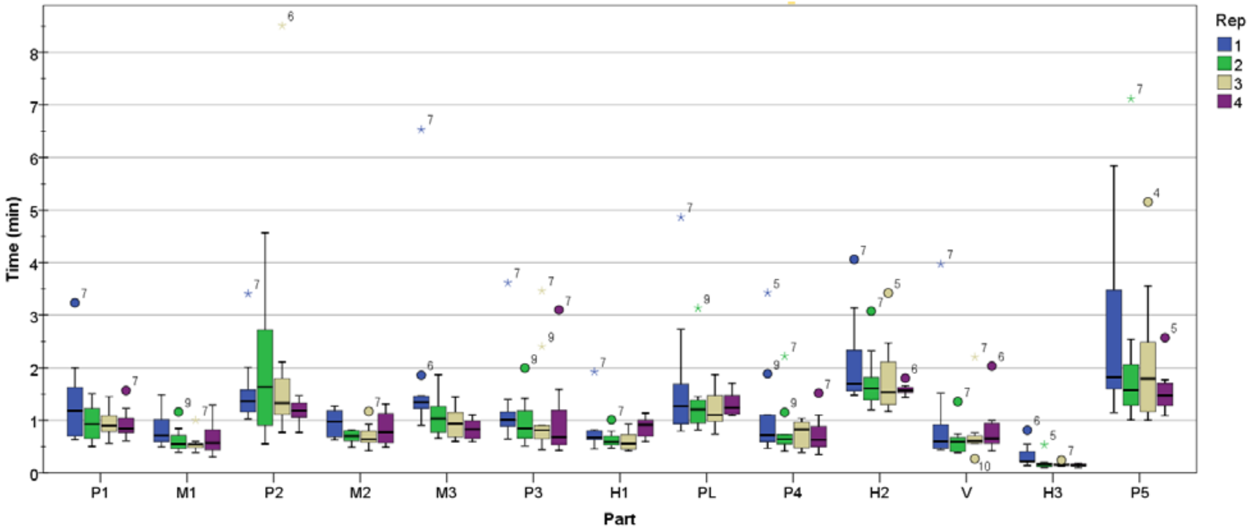


Fig. 2. Boxplot diagram of *VA* times of different parts.

As Table 3 and Fig. 2 show, the most installation time is spent on the large pipe parts (P2 and P5), the long hose part (H2), and the plate (PL). For these parts, in each repetition, the mean and median times are more than one minute. The biggest variations in installation times occur with P2 (with Rep 3, SD = 2.3) and P5 (with Rep 2, SD = 1.81). According to the observations made in the experiments, something that is typical of the problems with installing these large pipe parts is finding threads, which originate from problems with e.g. part alignment. The results and observations of installation problems in the present study are in line with [9], according to which assembly (installation) motions show a significant difference in performance between individuals.

Fig. 2 reveals the cause of the unusually long total installation times of the worst-performing pair (#7) at different repetitions. At least one marker of Pair #7 with each part confirms the fact that this pair had severe problems with installing different parts. For these participants, part alignment and finding threads caused permanent problems, despite the repetitions. In most of the problems, both the workers in that pair were present, which is further reflected in the long installation times.

When a part is being installed, in addition to the actual performance of a worker, the number of workers may affect the installation time. Table 4 shows the share of pairs in which both workers performed installation (*VA*) activities with different parts and repetitions (Rep).

Table 4. Share of pairs in which both workers performed installation (*VA*) activities with different parts and repetitions.

	N (Pairs)	P1	M1	P2	M2	M3	P3	H1	PL	P4	H2	V	H3	P5	AVERAGE
Rep 1	10	0.4	0.4	0.9	0	0.1	0.8	0.5	0.5	0.4	0.5	0.2	0.1	0.8	0.43
Rep 2	10	0.1	0.1	1	0	0	0.9	0.4	0.1	0.2	0.4	0.1	0.2	0.9	0.34
Rep 3	10	0.1	0.1	0.9	0	0	0.8	0.3	0.2	0.2	0.3	0.1	0.2	0.7	0.30
Rep 4	7	0	0.14	0.86	0	0	0.43	0.29	0	0	0.29	0	0.14	1	0.24
Total	9.25	0.15	0.19	0.91	0	0.03	0.73	0.37	0.2	0.2	0.37	0.1	0.16	0.85	0.33

As Table 4 shows, on average, collaboration in installing different parts decreases (0.43 to 0.24) as the number of repetitions increases. This indicates specialization and learning of workers in their dedicated parts and subtasks. Collaboration with part installation is most likely to occur with the large pipe parts, P2 and P5 (through different repetitions, average probabilities of 0.91 and 0.85). In addition, as observed in the experiments, P5 and P3 (average of 0.73) were typically installed at the end of the process, when there are few unfinished subtasks and thus collaboration is most likely to occur. From the different types of parts, the pipes and the hoses are the easiest for two workers to install simultaneously because there are two installation ends with these parts. On the other hand, with smaller parts, such as M1, M2, and M3, it is more difficult because of space limitations. It is noteworthy that collaboration can occur not only in simultaneous activities but also through the sequential activities of different workers.

Pearson correlation analysis was carried out in order to investigate the strength of the linear association between collaboration on installing the part and part installation time. For each part and repetition (41 cases where in at least one of the pairs the workers collaborated), the analysis revealed a total of nine significant (2-tailed, $p < 0.05$) correlations. The cases where severe problems with installation occurred were excluded. In the two remaining representative cases (for M1 with Rep 1, $r = 0.847$, $p < 0.002$, and for PL with Rep 3, $r = 0.811$, $p < 0.004$) there was a strong positive correlation. In these cases, when collaboration occurred, typically, one worker supported the part while the other installed it. This shows that collaboration may significantly increase the assembly time for smaller parts (such as M1 and PL), in which case collaboration on such parts should be avoided.

Correlation analysis was also performed between the number of *VA* tasks per worker and the total *VA* time. The correlation was only found significant ($r = 0.658$, $p < 0.039$) at the first repetition. This analysis, however, did not take into account problems with installation. Therefore, in general, the number of collaborative tasks when installing parts did not correlate with the total installation time of the parts.

4.2. REQ times

As mentioned, the *REQ* time comprises the necessary picking and handling of parts, small parts, and tools, and necessary moving in the assembly cell. Similarly to *VA* activities, *REQ* activities are connected to specific assembly parts. Table 2 and Fig. 1(b) show that *REQ* times vary relatively little between worker pairs. *REQ* times also decrease on average and evenly through the repetitions. This is a direct consequence of learning assembly parts and their installation locations. An interesting thing is the relationship between the number of parts a worker contributes to (either *REQ* or *VA* activity) and the total *REQ* time. To this end, again, correlation analysis was carried out. Fig. 3 presents a scatter diagram, in which, for each pair and repetition, scatter plots of the *REQ* time and the average number of tasks contributed per worker are shown. To summarize the plots in different repetitions, a linear trend line for each repetition is shown.

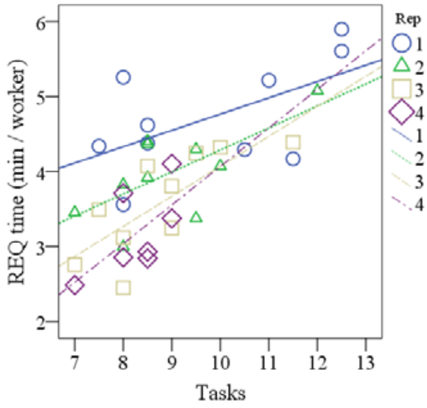


Fig. 3. Relationship between *REQ* time and the average number of tasks contributed per worker.

The analysis showed correlations of $r = 0.582$ ($p < 0.077$) with Rep 1, $r = 0.703$ ($p < 0.023$) with Rep 2, $r = 0.769$ ($p < 0.009$) with Rep 3, and, $r = 0.82$ ($p < 0.024$) with Rep 4. Thus, except with Rep 1, the correlation is statistically significant. The positive slopes of trend lines visualize the direction of relationships. As expected, the number of tasks a worker contributes will affect the *REQ* time. Further, the *REQ* time is reduced when workers specialize and avoid unnecessary collaboration on tasks.

5. Conclusions

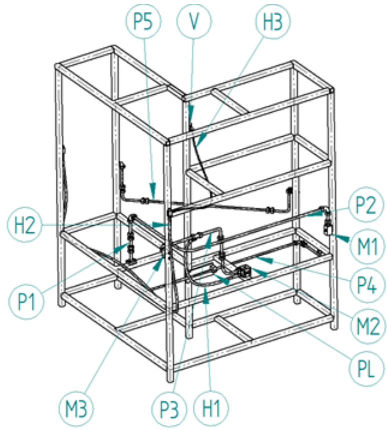
This paper studied the differences in performance between worker pairs in a case assembly task. On the basis of the results, the conclusions of this study are as follows:

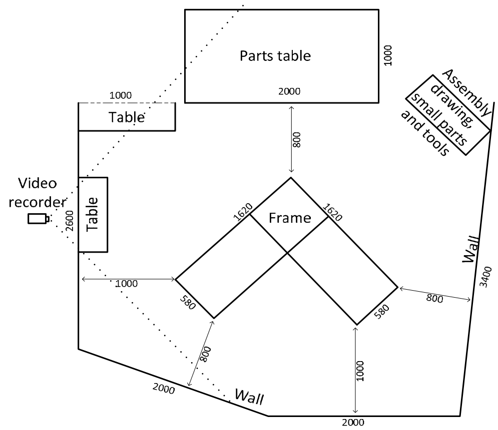
- performance varied significantly between pairs of workers. However, the relative variation between the pairs decreased through the repetitions. In each repetition, to assemble the product, the worst pair used at least twice as much time as the best pair;
- installation (value-adding) activities explained most of the variation in assembly time between the pairs;
- the variation in part installation times was most typically a consequence of problems with finding threads, which originated from problems with e.g. part alignment. Problems with installation motions can be eliminated through methods engineering;
- worker resources used on installing parts are consumed to a greater extent when both workers are present or help each other with an installation problem;
- correlation analysis showed that collaboration is not necessary with smaller parts as it will increase the installation time significantly with such parts;
- the number of tasks contributed by a worker affects the time required, i.e. time used for handling parts, tools, etc., and moving in the assembly cell. The time required is reduced when workers specialize and avoid unnecessary collaboration on tasks;
- the loss time and time used for reading instructions were large and varied a lot between the pairs at the first repetition. The significance of these times decreased rapidly as the workers learned through the repetitions;
- the rankings of the pairs of workers stayed relatively unchanged through the repetitions. Thus, within the given repetitions, there were permanent differences in performance between particular pairs. These differences can be minimized by paying attention to the selection of pairs.

In future research, since installation problems play a key role in differences, more detailed studies are needed to find out what makes the installation motions more challenging for some workers and pairs compared to others. When examining the differences between pairs of workers one should also consider the factors of learning, individual skills, and abilities, as well as the roles and communication of the workers. Another underlying question also is how to select workers in order to form the most suitable and effective pairs.

Appendix A. Parts list, case assembly product, and assembly cell layout

Item	Part name	Abbr.
(1)	Pipe 1	P1
(2)	Module 1	M1
(3)	Pipe 2	P2
(4)	Module 2	M2
(5)	Module 3	M3
(6)	Pipe 3	P1
(7)	Hose 1	H1
(8)	Plate	PL
(9)	Pipe 4	P4
(10)	Hose 2	H2
(11)	Valve	V
(12)	Hose 3	H3
(13)	Pipe 5	P5





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