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A framework for the continuous performance improvement of manned assembly lines

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This paper proposes a framework for the continuous performance improvement of manned assembly lines for major appliances. The suggested framework consists of two main activities: (1) assembly work process improvement, including time and motion study and (2) improvement of line balance efficiency. Although there have been numerous studies on this topic, most of them deal with partial issues rather than the continuous performance improvement of the whole assembly line, which this paper addresses. To develop the framework, we categorised a manned assembly line into five analysis levels, (*workstation, worker, operation cycle, work element* and *unit motion*), and identified user requirements on each level. Among these five analysis levels, the *workstation* level supports line balancing, while the other four (*worker, operation cycle, work element* and *unit motion*) address work process improvement. The proposed framework has been implemented and tested with various examples from Korean assembly line based manufacturers.

Keywords: continuous performance improvement; major appliances; manned assembly line; work process improvement; line balance

1. Introduction

The productivity of manufacturing systems is one of the most important elements for an enterprise's competitiveness. When a manufacturing system has been implemented, the enterprise must carry out continuous performance improvement to enhance the production efficiency of the systems in operation. This activity is mandatory for enterprises to maintain their competitiveness, because there are always productivity decline factors in the systems, such as worker/product changes, new technology development and process planning revision (Song, Ming, and Xu 2013).

A manned assembly line is one process of manufacturing that is better suited for manufacturing goods because of its greater flexibility when compared to an automated system. This process has been adopted in the electronic appliances industry, which has many product types and frequent process changes. A general manned assembly line process is comprised of three factors: worker, machine, and material (see Figure 1). After building all the equipment and operation plans of assembly lines, it is difficult to modify the layout or replace the equipment because the cost of modification is usually as much as the cost of the installation of facilities (e.g. equipment replacement costs, factory idling compensation and the required time, effort and risks involved in operation rescheduling). Therefore, the improvement of an installed assembly line focuses on efficiency maximisation via the continuous adjustment of already installed factors (Stevenson 2009).

For the continuous performance improvement of manned assembly lines for major appliances (i.e. televisions, air-conditioners and refrigerators), two activities (assembly work process improvement and improvement of line balance efficiency) are needed (see Figure 2). In a manned assembly line, assembly work process improvement focuses on the performance improvement of a workstation, which is dependent on the efficiency of the assembly work processes of the workers involved. Therefore, the elimination/minimisation of inefficiency in a work process is at the heart of the improvement sought by companies, by which the cycle time of a workstation can be reduced, thereby leading to productivity gains.

The improvement of line balance efficiency focuses on workload balancing of workstations in an assembly line structured as conveyor belts for massive production. A manned assembly line is formed by sequentially aligned multiple workstations. Thus, the takt time (the cycle time of an assembly line) is decided by a 'dominant workstation', which is the one that has the longest cycle time within an assembly line. Line balance efficiency is an indicator that represents the degree of balance between workloads on various workstations. To increase the line balance efficiency, the work of the dominant workstation has to be reallocated to idle workstations to reduce the takt time.

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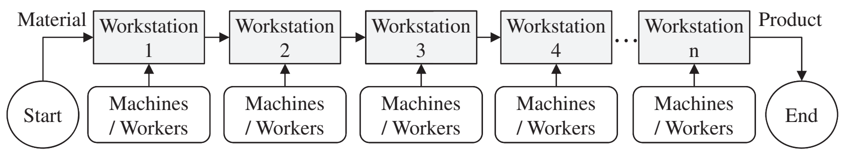


Figure 1. Assembly line structure.

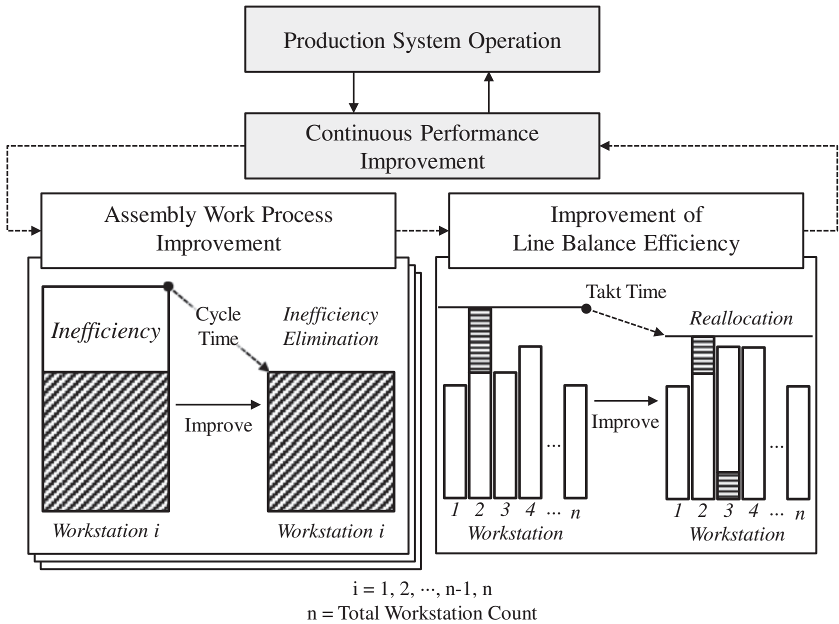


Figure 2. Continuous performance improvement of manned assembly lines.

Existing research regarding the performance improvement of manufacturing systems can be categorised as follows: (1) manufacturing system design, (2) manufacturing operation management and (3) work process design. The first category, manufacturing system design, pertains to research on design operation processes, capacity plans, equipment installation layout and material delivery plans (Smith 2003). This field has been studied to determine the optimal structure of an operation process (i.e. job shop, batch, assembly and continuity) based on capacity plans, such as the quantity of production, diversity of product types and flexibility of production equipment (Bazargan-Lari 1999; Yang, Peters, and Tu 2005). The chosen operation process is applied to the design of the equipment installation layout (Deb and Bhattacharyya 2005) and material delivery planning (Lin and Chu 2013). This element of the process is considered before system implementation based on long-term decision-making (Hasan, Sarkis, and Shankar 2012). Therefore, manufacturing system design does not belong in the research area of continuous performance improvement of running systems, which is the area of focus of this paper.

However, the second and third research categories pertain to performance improvement after system implementation. Manufacturing operation management consists of research for the optimisation of system operation planning (Baker 2013) and resource scheduling (Cesani and Steudel 2005; Herrmann et al. 1995). In this field, many approaches such as stochastic programming (Das, Baki, and Li 2009), heuristic algorithms (Mejía and Odrey 2005; Syarif and Gen 2003) and computer simulation methods (Park and Chang 2012) have been researched and applied. Because manned assembly lines for major appliances mostly have sequential workflows and simple plans are required for the operational processes and resource scheduling. Therefore, similar to manufacturing system design, this research field is not related to the objective of this paper.

The third field, work process design that is suitable for this paper, pertains to research on designing efficient manufacturing processes. This research has been applied to automated and manned manufacturing systems. For the automated manufacturing system, much research has been done on automated process planning (Lee et al. 1998; Pan et al. 2008) and robot OLP (OffLine Programming) for machine work process planning, involving processes such as cutting, welding and casting (Park and Chung 2003; Ruan, Eiamsaard, and Liou 2005). For the manned manufacturing system, many approaches have been studied, such as macro/micro-motion study, time study and ergonomics. These approaches analyse an operator's work process to eliminate inefficiency in the operator's movements (Cuatrecasas, Fortuny, and Vintro 2011; Dağdeviren, Eraslan, and Çelebi 2011; Finnsgård et al. 2011; Freivalds and Niebel 2009). For both types of manufacturing systems, the workflow is a very important factor that determines the performance of a system, because inefficient workflows can lead to bottlenecks, which are the main cause of performance decline. Workload balancing of work processes is an effective approach to stabilise the workflows of a system (Barutcuoglu and Azizoglu 2010).

Despite considerable research regarding the performance improvement of manufacturing systems, existing relevant studies have dealt with only system optimisation methodologies or partial improvement for motion efficiency. To fill this research gap, the paper's main objective is to propose a framework for the continuous performance improvement of manned assembly lines for major appliances. The proposed framework includes both the macro (system) and micro (motion) aspects of the system, and achieves the two proposed activities (assembly work process improvement and the improvement of line balance efficiency). The proposed framework has been implemented and tested with examples from manufacturers in Korea.

The overall structure of this paper is as follows. Section 2 contains a description of the study's technical approach, and the proposed framework for continuous performance improvement is explained in Section 3. The implementation result is presented with an example in Section 4. Finally, the conclusion of this paper is provided in Section 5.

2. Technical approach

A manned assembly line for major appliances is formed by multiple workstations linked with conveyor belts; work on a workstation is performed by one or more workers. Each worker executes one operation repetitively; therefore, an operation cycle means a single, repetitive execution of an operation. An operation cycle consists of several work elements, which are composed of various unit motions. Because operations on a workstation are repetitive, every operation and work element is composed of similar work elements and unit motions. According to the aforementioned structure of a manned assembly line, this paper proposes a five-level decomposition model as depicted in Figure 3; the definitions of the terminologies in this model are explained in Table 1.

In each level of the decomposition structure, different analysis issues were derived from the user requirements of manufacturing fields, as explained in Table 2. Four analysis levels (*worker, operation cycle, work element* and *unit motion*) address issues relevant to a single workstation, and the last analysis level (*workstation*) pertains to issues related to a set of workstations. For the two activities of continuous performance improvement, the proposed framework consists of two functions (*workstation analysis* and *line analysis*). The workstation analysis function supports assembly work process improvement on the first four analysis levels; the line analysis function supports the improvement of line balance efficiency on the last analysis level. This relationship, which stretches from the analysis issues to system functions, is described in Figure 4.

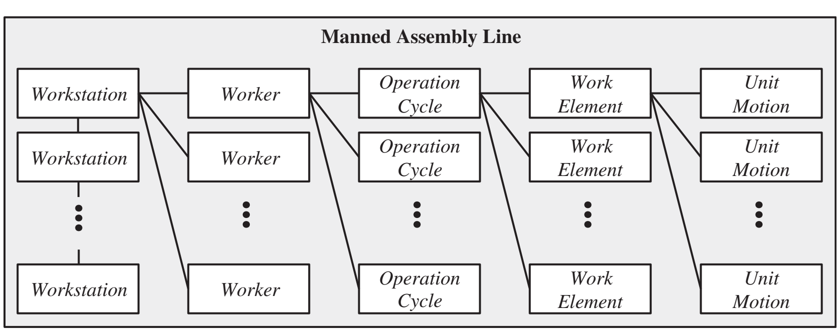


Figure 3. 5-level decomposition model.

Table 1. Definitions of terminologies.

Terminology	Description	Example
Workstation	A workstation is a place for execution of one function from operations that are decomposed to manufacture products of an assembly line in a sequential manner	Back panel component assembly Attachment of the main LED component LED module attachment
Worker	Workers (single or multiple) are the operators that execute an operation of a workstation	Worker 1 Worker 2 Worker 3
Operation cycle	Operation on a workstation is repetitive; therefore, it has many cycles. An operation cycle means a single, repetitive execution of an operation	1st cycle 2nd cycle 3rd cycle
Work element	A work element is a unit for dividing an operation, and it represents a macro motion of an operator	Connect a cable to a panel Prepare a resource Allocate a resource on a panel
Unit motion	A unit motion is a unit for dividing a work element, which represents a micro motion of an operator	Hold a power screwdriver Move a power screwdriver Tighten a screw to fix a part

Table 2. Details of analysis issues.

No.	Analysis issue	Description
1	Identify workstations causing line balance inefficiency	Line balance efficiency is an indicator of the workload allocation efficiency of an assembly line. Inefficient line balance implies that workloads are not efficiently distributed between workstations, and should therefore be reallocated
2	Identify workstations of inconsistent cycle time	An unstable workstation, which has considerable variance in cycle time, can be assumed to include operation cycles that are not standardised. Therefore, operation cycles of the workstation should be standardised to have similar time
3	Identify workstations that have imbalanced cycle time	All operation performed by workers in one workstation should have similar cycle time. Thus, work processes of workers that have imbalanced cycle time should be redesigned efficiently to reduce the overall cycle time of a workstation
4	Identify work elements of inconsistent work time	An unstable work element, which has considerable variance in work time, is assumed to contain unit motions of the work element that are not standardised. Therefore, the work element should be standardised to have similar measured time
5	Identify inefficient work elements	A work element that is identified as being inefficient is required to be eliminated from the work process. For example, waiting for the next part/inspecting the defects of a part
6	Identify inefficient unit motions	A unit motion that is identified as being inefficient is required to be eliminated from the unit motions of the work element. For example, rearranging a part/moving a driver/bringing a screw
7	Identify incompatible unit motions within a PTS system	A unit motion that is incompatible with a motion time defined in a PTS (Predetermined Time Standard) system is required to be inspected

This paper proposes two analysis tables to support each function of the framework. The one for workstation analysis is designed to record the analysis results of a user, while the other is meant for line analysis, which integrates the analysis results of various workstations. The workstation analysis table presented in Table 3 represents the work process of a worker as unit motions, work elements, operation cycles and inefficiency in the work process. Each column of the table is explained as follows, and operation cycles are specified by a thick line below the first work element row in the table.

- Work Element: Definition of a work element ID.
- WE (Work Element) Type: Definition of a work element type using the following five symbols:
  - O: Operation to change characteristics of the material.
  - →: Move; transporting the material from one place to another.

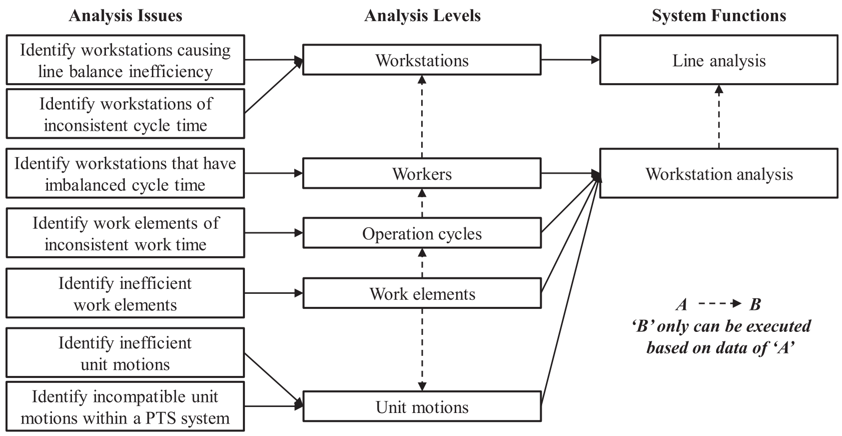


Figure 4. Relationship between analysis issues and functions.

Table 3. Workstation analysis table.

No.	Work Element	WE Type	Unit Motion	VA Type	Waste Type	Start Time	Interval Time	MOD
1								
2								

- ○ ∇: Storage; when the material is kept in any location.
- ○ D: Delay; when the material cannot go to the next activity.
- ○ □: Inspection to check the quality or quantity of the material.
- Unit Motion: Definition of a unit motion ID.
- Value Added (VA) Type: Definition of a unit motion as the following three types:
  - VA (Value Added): A unit motion that relates to product manufacturing.
  - BVA (Business Value Added): A necessary unit motion that is not related to product manufacturing.
  - NVA (Non-Value Added): An unnecessary unit motion.
- Waste Type: Definition of a waste type of a unit motion identified as BVA or NVA.
  - Waste types that are defined in TPS (Toyota Production System), such as processing, movement, making defective products, transportation, waiting, overproduction and stockpile.
- Start Time: Start time of a unit motion.
- Interval Time: Duration of a unit motion.
- MOD: A PTS analysis result of a unit motion using MODAPTS (MODular Arrangements of Predetermined Time Standards).

The line analysis table presented in Table 4 represents the cycle time distribution and work elements of each workstation in an assembly line by columns as follows:

- Workstation: Represents the workstation ID.
- Worker: Represents a current worker of a workstation.
- Work element: Represents a work element executed in a workstation.
- VA, BVA, & NVA time: Represents a value added type of work element.
- CT (Cycle Time): Represents the average operation time of a workstation.
- Min: Represents the minimum operation time of a workstation.

Table 4. Line analysis table.

No	Work-station	Worker	Work Element	WE Type	VA Time	BVA Time	NVA Time	CT	Min	Max	Med	1/4	3/4	Avg
1														
2														

- Max: Represents the maximum operation time of a workstation.
- Med: Represents the median operation time of a workstation.
- 1/4: Represents the quarter-ranked operation time of a workstation.
- 3/4: Represents the three-quarter-ranked operation time of a workstation.
- Avg: Represents the average operation time of a workstation (excluding the Min and Max values).

3. Framework

The two functions of the proposed framework are constructed as follows. The workstation analysis function consists of three components: a work-recorded video playback, the workstation analysis table and an analysis result presentation. This function allows a user to analyse work processes in a workstation from various perspectives repeatedly, while watching a work-recorded video (Chang et al. 2003; Forsman et al. 2002; Hanse and Forsman 2001). The user then records the analysis results on the table and the recorded results are visualised. A detailed procedure for the workstation analysis is described below.

3.1 *Workstation analysis procedure*

(1) A user of the system watches a work video several times until the recorded work can be understood.
(2) The user inputs a command to generate sections in the video representing various work elements. The work element has a time range that starts from an end time point of the former work element section and finishes up in the command input time point. If the time point is not on the time range of any work element section, a time point of the video at the command input generates a section for a work element. Therefore, work elements are inserted sequentially into the workstation analysis table. This section generation process is explained in Figure 5.

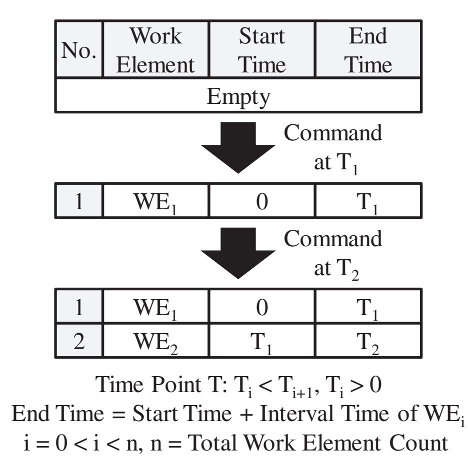


Figure 5. Section generation process for a work element.

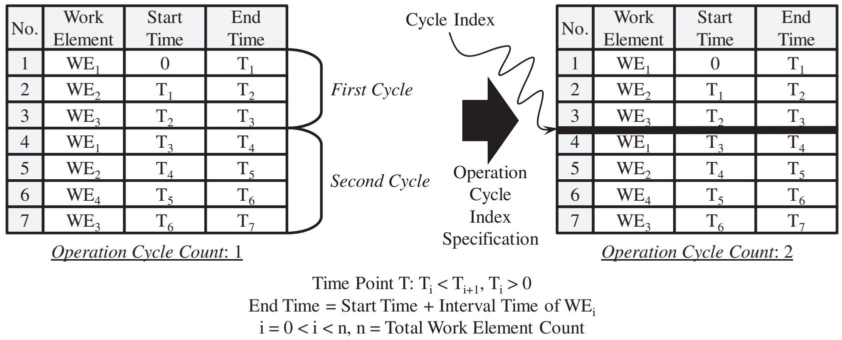


Figure 6. Operation cycle identification process.

(3) Sequentially recorded work elements on the workstation analysis table have patterns because the work on a workstation is a repetitive operation. Although each operation is not represented as an exactly equal combination of work elements, there is a trend of work elements that helps to identify the beginning and end of a single operation cycle. Thus, the operation cycle identification process is one in which a user specifies the beginning of every operation cycle as described in Figure 6.

(4) A work element, when generated, has one unit motion. If the time point of a video at an input command is on the time range of a unit motion section, the unit motion is separated into two parts by the time point: (1) one that begins from the start time of a current unit motion and finishes at the command inputted time point and (2) another that starts from the command inputted time point and finishes at the end time of a current unit motion. The section generation process for unit motion is explained in Figure 7.

(5) A unit motion is categorised into a set of basic human motions (i.e. grasp an object) of MODAPTS, and the standard time required for them is also defined therein. Therefore, analysing a unit motion using MODAPTS helps to uncover inefficiencies in the unit motion by calculating the standard motion time and comparing it with the measured time.

The work processes identified by the workstation analysis are interpreted to reveal inefficiencies in workers, operation cycles, work elements and unit motions. The analysis result presentation enables the interpretation using charts. The interpretation methods for the analysis levels of this function are explained below.

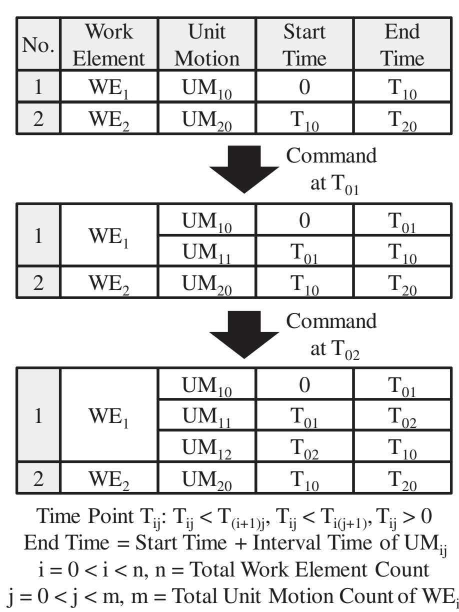


Figure 7. Section generation process for a unit motion.

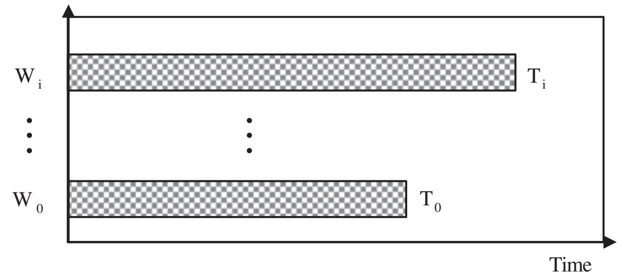


Figure 8. Presentation of a single bar chart.

3.2 *Interpretation of the workstation analysis result*

3.2.1 *Analysis of work elements*

Work elements that are not defined by the WE type as ‘O’ in the work analysis procedure are inefficient, and cause time delays in a standard operation cycle. Therefore, such work elements should be identified to improve the standard operation. The method to identify inefficient work elements is represented by a time composition of operations by work elements and WE type using a single bar chart as described in Figure 8; the chart is constructed by Functions (1) and (2).

(1) Function for the time composition by work elements

$$T_i = \sum_{j=1}^{n} (\mathrm{TE}_{ij})$$

W_i: ith work element ID
T_i: Total time of W_i
TE_{ij}: Time of W_i at operation cycle j
i: $0 < i <$ Total count of work element IDs
n: Total cycle count

(2) Function for the time composition by WE type

$$T_i = \sum_{j=1}^{n} \sum_{k=1}^{m} (if\,(\mathrm{WT}_{kj} = W_i) : \mathrm{TE}_{kj} || else : 0)$$

W_i: ith WE type
T_i: Total time of W_i
TE_{kj}: Time of the kth work element at operation cycle j
WT_{kj}: Type of the kth work element at operation cycle j
i: $0 < i <$ Total count of WE types $= 5$
n: Total cycle count
m: Number of work elements at cycle j

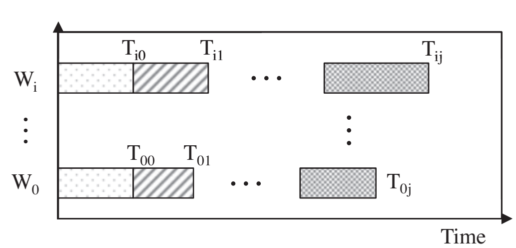


Figure 9. Presentation of a cumulative bar chart.

3.2.2 *Analysis of unit motions*

Unit motions that are identified as BVA or NVA in the work analysis procedure are inefficient and are responsible for time delays in a work element. Therefore, they need to be identified to improve the standard unit motions of a work element. The method to identify inefficient unit motions involves the presentation of time compositions of work elements by VA types and waste types using a cumulative bar chart as described in Figure 9; the chart is constructed by Function (3).

(3) Function for the time composition by the VA types or waste types

$$T_{ij} = \sum_{k=1}^{n} \sum_{l=1}^{m} (\text{if } (\text{UT}_{ikl} = \text{TP}_j) : \text{TU}_{ijk} || \text{else} : 0)$$

W_i: ith work element ID
TP: (VA type or waste type)
TP_j: jth TP
T_{ij}: Time of the TP_j of the ith work element ID
UT_{ijk}: TP of the kth unit motion in W_i at operation cycle j
TU_{ijk}: Time of kth unit motion in W_i at operation cycle j
n: Total cycle count
m: Number of unit motions in W_i at cycle k

A unit motion that was not identified as an inefficient factor is able to contain inefficiency related to basic motions. Such a unit motion is detected by comparison of actual motion time and standard motion time computed by the MODAPTS analysis.

3.2.3 *Analysis of operation cycles*

Considerable variance in the work time of one work element ID indicates that unit motions of the work element are not standardised. Highly varied work time is caused by non-uniform unit motions that occasionally appear in work elements or irregularly take up time in every execution. Therefore, distribution of work time must be identified to standardise non-uniform unit motions of a work element. The method to identify the distribution is presentation using a box plot chart (see Figure 10) constructed by Function (4).

(4) Function for the box plot chart of work time distribution
W_i: ith work element ID
S_i: Set of work time of work elements of W_i in ascending order
N_i: Number of values in S_i
T_{i0}: Minimum value of $S_i = S_i[1\text{st}]$
T_{i1}: 1st quartile value of $S_i = S_i[(N/4)\text{th}]$

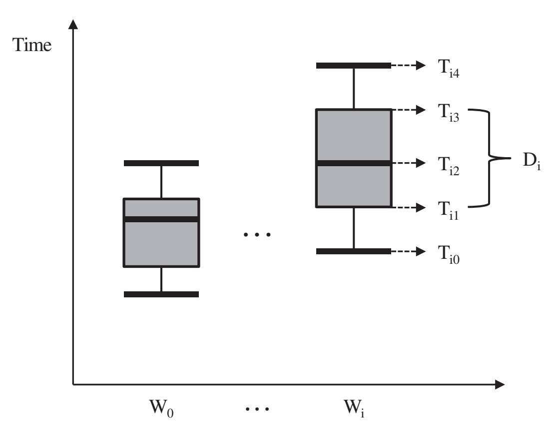


Figure 10. Presentation of a box plot chart.

T_{i2}: Median value of $S_i = S_i[(N/2)\text{th}]$
T_{i3}: 3rd quartile value of $S_i = S_i[(3\,N/4)\text{th}]$
T_{i4}: Maximum value of $S_i = S_i[N\text{th}]$
D_i: Deviation of work time in S_i

3.2.4 *Analysis of workers*

The cycle time of a workstation is deemed to be the longest cycle time among work processes of workers. An imbalance in the cycle time of workers implies that the workloads of a workstation are not properly assigned among the workers. Accordingly, the cycle time of a workstation can be improved by redesigning the work processes for workload balancing. Therefore, cycle time balance among workers should be identified, and a suitable method is presented using a cumulative bar chart (see Figure 9). This chart represents the time composition of standard work processes by work elements, WE type, VA type and waste type; it has been constructed by Function (5).

(5) Function for the time composition in a standard operation process

$$T_{ij} = 1/n\ \sum_{k=1}^{n} \sum_{l=1}^{m} (\text{if }(\text{UT}_{ikl} = \text{TP}_j) : \text{TU}_{ijk} || \text{else} : 0)$$

(5-a) TP: (Work element ID or WE type)
(5-b) TP: (VA types or waste types)
W_i: *i*th worker
TP_j: *j*th TP
T_{ij}: Time of the TP_j in a standard operation process of the *i*th worker
n: Total cycle count
m: Number of work elements in W_i at cycle *k*
(5-a)
UT_{ijk}: TP of the *k*th work element at operation cycle *j* of W_i
TU_{ijk}: Time of *k*th work element at operation cycle *j* of W_i
(5-b)
UT_{ijk}: TP of the *k*th unit motion at operation cycle *j* of W_i
TU_{ijk}: Time of *k*th unit motion at operation cycle *j* of W_i

The line analysis function consists of three components: the line analysis table, an analysis result presentation and reallocation assessment. The function constructs a virtual manned assembly line based on the line analysis table, which is generated by the conversion of workstation analysis results. The analysis result presents the performance and inefficiency of the virtual line. The reallocation assessment allows a user to reallocate work elements to improve the performance of the line. For the construction of the virtual line, analysis results of workstations are converted to the line analysis table. Each workstation analysis result is converted for the representation of overall performance using Function (6) and a detailed time composition using Function (7).

(6) Conversion function for overall performance of a workstation

$$\text{CT} = 1/n \sum_{j=1}^{n} S_i$$

Min = S[1st]
Max = S[*n*th]
Med = S[(*n*/2)th]
1/4 = S[(*n*/4)th]
3/4 = S[(3*n*/4)th]
$\text{Avg} = 1/(n-2)\ \sum_{i=2}^{n-1} S_i$
S: Set of operation cycle time
S_i: *i*th operation cycle time
n: Number of operation cycles

(7) Conversion function for detailed time composition of a workstation

VA Time of $W_i = 1/n \ \sum_{k=1}^{n} \sum_{l=1}^{m} (\text{if } (\text{UT}_{ikl}) = \text{VA}) : \text{TU}_{ijk} || \text{else} : 0)$

BVA Time of $W_i = 1/n \ \sum_{k=1}^{n} \sum_{l=1}^{m} (\text{if } (\text{UT}_{ikl}) = \text{BVA}) : \text{TU}_{ijk} || \text{else} : 0)$

NVA Time of $W_i = 1/n \ \sum_{k=1}^{n} \sum_{l=1}^{m} (\text{if } (\text{UT}_{ikl}) = \text{NVA}) : \text{TU}_{ijk} || \text{else} : 0)$

W_i: ith work element ID

UT_{ijk}: VA type of the kth unit motion in W_i at operation cycle j

TU_{ijk}: Time of kth unit motion in W_i at operation cycle j

n: Total cycle count

m: Number of unit motions in W_i at cycle k

The line analysis table is interpreted to represent performance (takt time and line balance efficiency of an assembly line) and inefficiency (inconsistent cycle time of workstations) regarding the analysis level of workstations using analysis result presentation. The interpretation methods are explained below.

3.3 *Interpretation of the analysis of workstations*

3.3.1 *Workstations of inconsistent cycle time*

Considerable variance in cycle time of a workstation indicates that its work elements are not standardised. Such a situation is the result of non-uniform work elements that appear in operation cycles occasionally or take up time irregularly in every execution. Therefore, the distribution of cycle time must be identified to standardise non-uniform work elements of the standard operation cycle of a workstation. The method to identify the distribution is presentation using a box plot chart (see Figure 10) constructed by Function (8) based on the line analysis table.

(8) Function for the box plot chart of cycle time distribution

W_i: ith workstation ID

T_{i0}: Value in 'Min' column of W_i

T_{i1}: Value in '1/4' column of W_i

T_{i2}: Value in 'Med' column of W_i

T_{i3}: Value in '3/4' column of W_i

T_{i4}: Value in 'Max' column of W_i

D_i: Deviation of cycle time in W_i

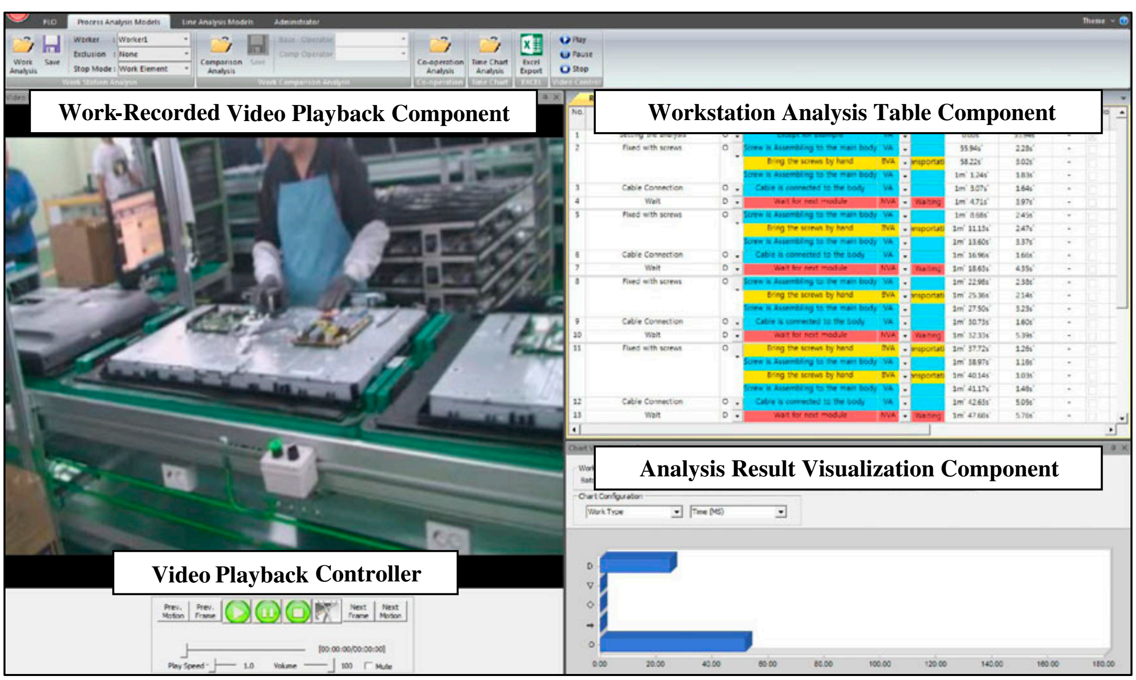
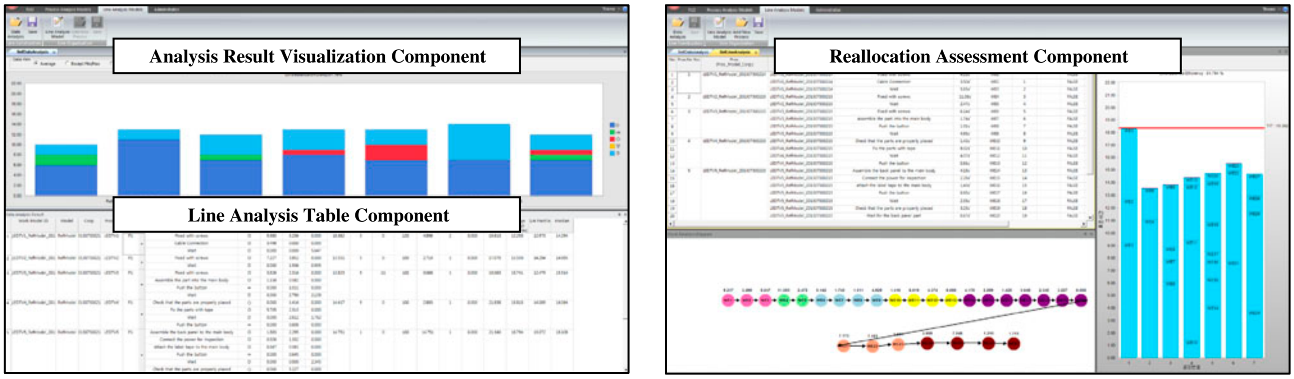


Figure 11. Workstation analysis function.



(a) Components for the line analysis table and analysis result visualization

(b) Reallocation assessment component

Figure 12. Line analysis function.

No.	Work Element	Work Type	Unit Motion	VA Type	Waste Type	Start Time	Time Interval	MOD	Exclusion
1	Except	O	Except	VA		0.00s'	55.63s'	-	
2	Assemble the back panel to the main body	O	Bring the back panel	BVA	Transportation	55.63s'	2.76s'	13	
			Assemble the back panel to the main body	VA		58.39s'	2.02s'	8	
3	Connect the power for inspection	O	Bring the power cable to main body by right hand	BVA	Transportation	1m' 0.42s'	1.73s'	10	
			Connect the power cable to back panel	VA		1m' 2.15s'	1.28s'	10	
4	Attach the label tape to the main body	O	Bring the label tape to main body by left hand	BVA	Transportation	1m' 3.43s'	0.73s'	6	
			Attach the label tape to main body	VA		1m' 4.16s'	0.80s'	5	
5	Push the button	⇒	Push the move button by left hand	BVA	Transportation	1m' 4.96s'	1.01s'	4	
6	Wait	D	Wait for a next part	NVA	Waiting	1m' 5.97s'	2.73s'	-	
7	Check that the parts are properly placed	◇	Check that the parts are properly placed	BVA	Etc.	1m' 8.71s'	4.53s'	3	
8	Assemble the back panel to the main body	O	Bring the back panel	BVA	Transportation	1m' 13.24s'	2.01s'	13	
			Assemble the back panel to the main body	VA		1m' 15.25s'	3.25s'	8	
9	Connect the power for inspection	O	Bring the power cable to main body by right hand	BVA	Transportation	1m' 18.50s'	1.76s'	10	
			Connect the power cable to back panel	VA		1m' 20.26s'	0.75s'	10	
10	Attach the label tape to the main body	O	Bring the label tape to main body by left hand	BVA	Transportation	1m' 21.01s'	0.73s'	6	
			Attach the label tape to main body	VA		1m' 21.74s'	1.02s'	5	
11	Push the button	⇒	Push the move button by left hand	BVA	Transportation	1m' 22.77s'	0.78s'	4	
12	Wait	D	Wait for a next part	NVA	Waiting	1m' 23.55s'	2.79s'	-	
13	Check that the parts are properly placed	◇	Check that the parts are properly placed	BVA	Etc.	1m' 26.34s'	4.53s'	3	
14	Assemble the back panel to the main body	O	Bring the back panel	BVA	Transportation	1m' 30.87s'	4.01s'	13	
			Assemble the back panel to the main body	VA		1m' 34.88s'	1.75s'	5	
15	Connect the power for inspection	O	Bring the power cable to main body by right hand	BVA	Transportation	1m' 36.63s'	1.24s'	10	
			Connect the power cable to back panel	VA		1m' 37.87s'	1.27s'	10	
16	Attach the label tape to the main body	O	Bring the label tape to main body by left hand	BVA	Transportation	1m' 39.14s'	0.48s'	6	
			Attach the label tape to main body	VA		1m' 39.63s'	1.25s'	5	
17	Push the button	⇒	Push the move button by left hand	BVA	Transportation	1m' 40.88s'	0.79s'	4	
18	Wait	D	Wait for a next part	NVA	Waiting	1m' 41.66s'	2.79s'	-	

Figure 13. Workstation analysis table result.

3.3.2 *Workstations causing inefficient line balance*

Line balance efficiency represents workload allocation efficiency as the ratio of the average cycle time of workstations and the takt time of an assembly line. Inefficient line balance results when there is significant difference between the cycle time of the dominant workstation and the average cycle. In this situation, the takt time is delayed by inefficiently allocated workload on a dominant workstation. Therefore, line balance efficiency should be identified to improve the takt time; the method for this is presented using a cumulative bar chart (see Figure 9) to represent the time composition of each workstation by WE type or VA type using Functions (9) and (10) based on the line analysis table.

(9) Function for the time composition by WE type in a workstation

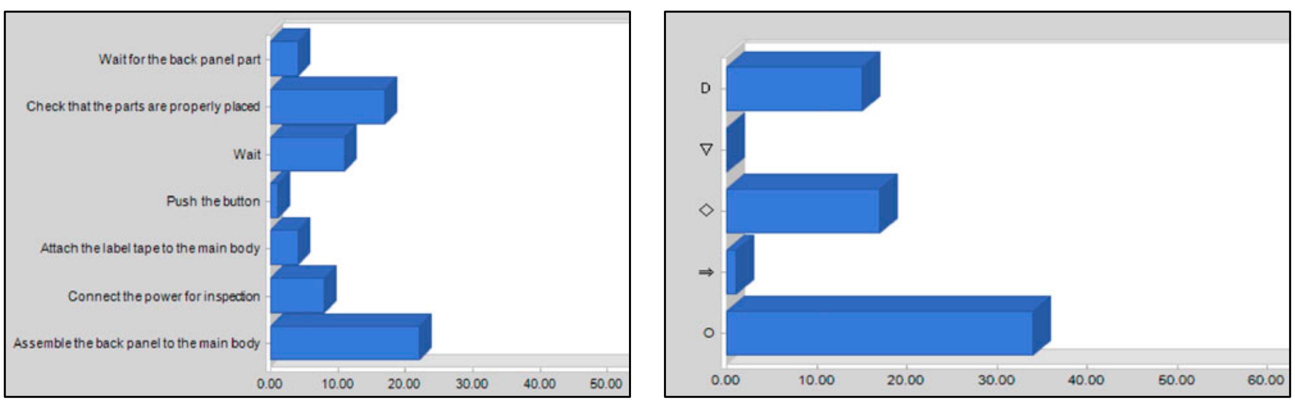
$$T_{ij} = \sum_{k=1}^{n} (\text{if } (\text{UT}_{ij}) = \text{TP}_j) : \text{TU}_{ik} || \text{else} : 0)$$

W_i: ith workstation
TP_j: jth WE type
n: Number of work elements in W_i
T_{ij}: Time of the TP_j of the W_i
TU_{ij}: Sum of values in columns of ‘VA’, ‘BVA’, and ‘NVA’ of jth work elements of W_i
UT_{ij}: Value in ‘WE type’ column of the jth work element in W_i

(10) Function for the time composition by VA type in a workstation

$$T_{ij} = \text{TU}_{ijk}$$

W_i: ith workstation



(a) Time composition by work elements (b) Time composition by WE types

Figure 14. Interpretation result of work elements.

(a) Time composition by VA types (b) Time composition by waste types

Figure 15. Interpretation result of unit motions.

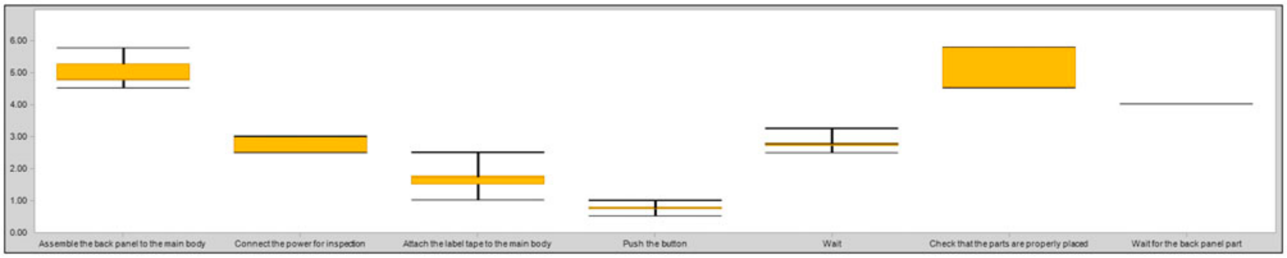
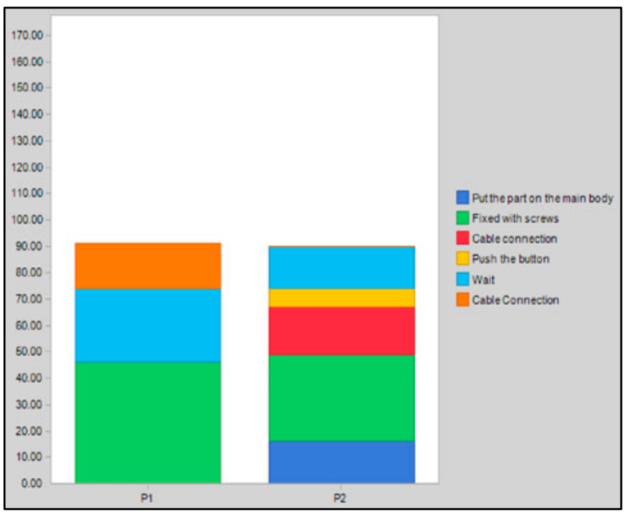
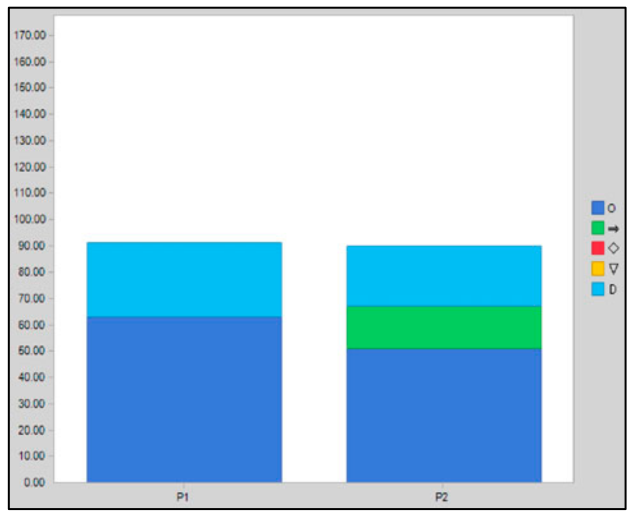


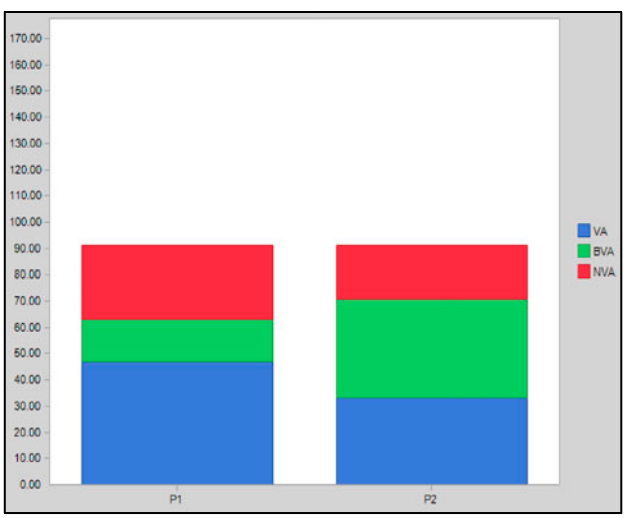
Figure 16. Interpretation result of operation cycles.



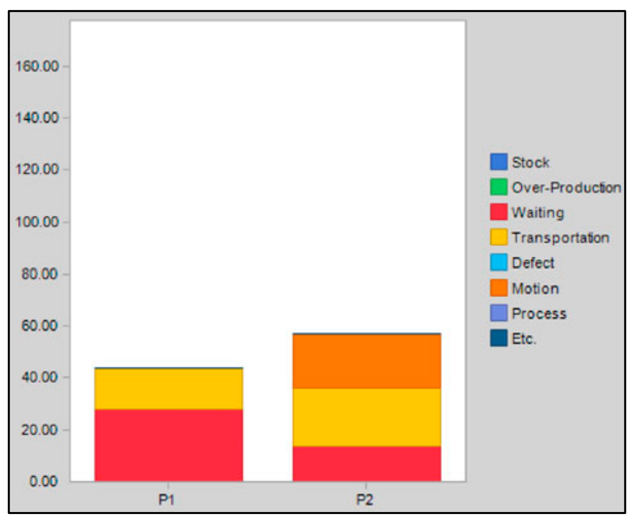
(a) Time composition by work elements



(b) Time composition by WE types



(c) Time composition by VA types



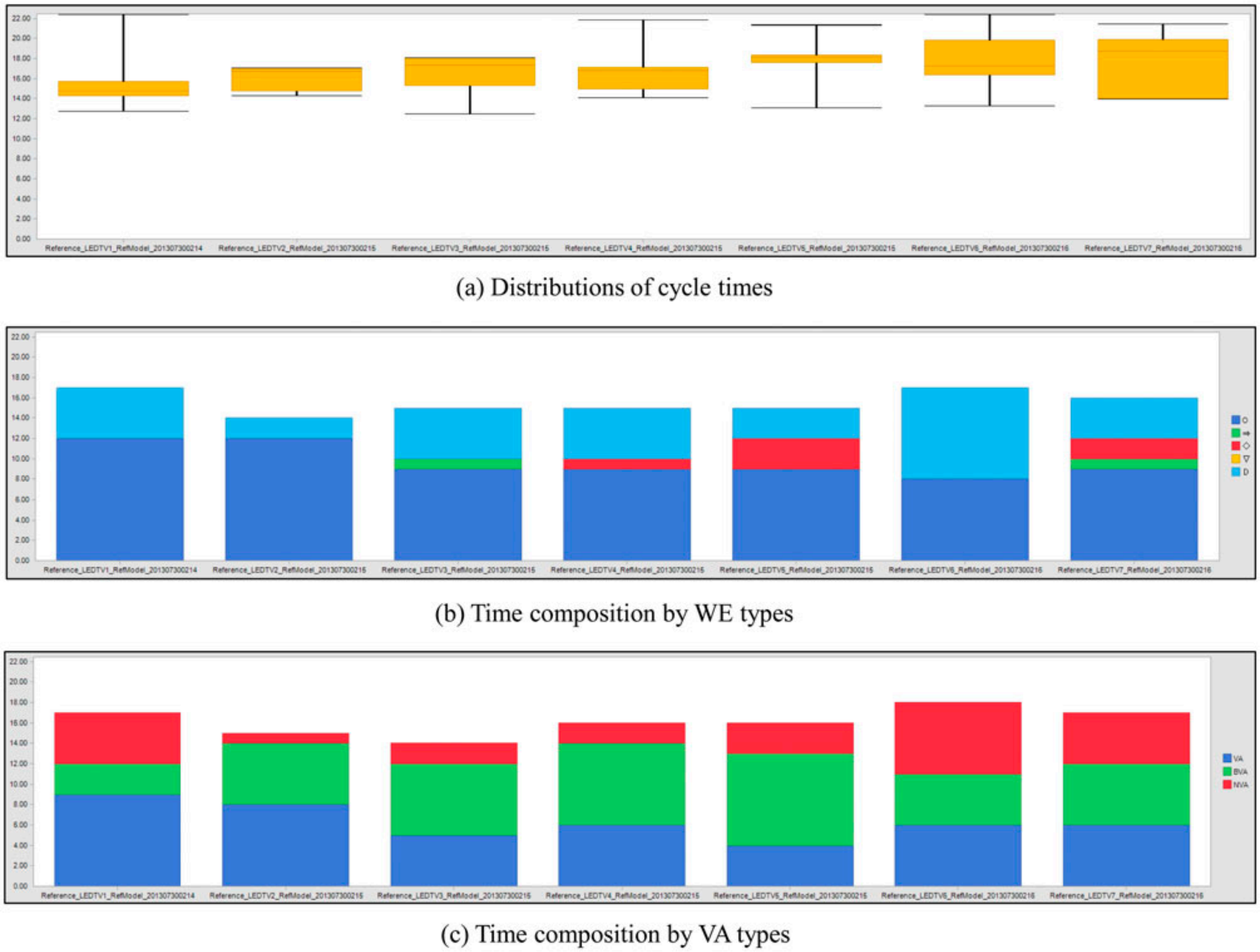
(d) Time composition by waste types

Figure 17. Interpretation result of workers.

Data Analysis Result

	Work Model ID	Model	Corp.	Process	Operator	Work Element	Work Type	VA	BVA	NVA	Average	Batch Size	Defect Ratio(%)	Skill Level(%)	Average (Work Spec. Base)	Operator Count	Min.	Max.	Average (Except Min&Max)	1/4 Fractile	Median	3/4 Fractile
1	LEDTV1_RefModel_201	RefModel	0130730021	LEDTV1	P2	Put the part on the main body	⇒	0.000	2.116	0.000	11.519	1	0	100	11.519	2	12.740	34.309	14.923	14.300	14.740	15.729
						Fixed with screws	O	1.989	2.151	0.000												
						Cable connection	O	2.201	0.157	0.000												
						Push the button	D	0.000	0.000	0.879												
						Wait	D	0.000	0.395	1.629												
2	LEDTV2_RefModel_201	RefModel	0130730021	LEDTV2	P1	Fixed with screws	O	7.227	3.852	0.000	13.551	5	0	100	2.710	1	0.000	17.070	15.559	14.294	14.995	17.044
						Wait	D	0.000	1.536	0.935												
3	LEDTV3_RefModel_201	RefModel	0130730021	LEDTV3	P1	Fixed with screws	O	3.826	2.316	0.000	13.823	5	11	100	3.068	1	0.000	18.063	15.741	12.479	15.514	18.039
						Assemble the part into the main body	O	1.158	0.582	0.000												
						Push the button	⇒	0.000	1.011	0.000												
						Wait	D	0.000	2.790	2.139												
4	LEDTV4_RefModel_201	RefModel	0130730021	LEDTV4	P1	Check that the parts are properly placed	◇	0.000	1.416	0.000	14.417	5	0	100	2.883	1	0.000	21.838	15.818	14.089	16.064	17.147
						Fix the parts with tape	O	5.705	2.313	0.000												
						Wait	D	0.000	2.612	1.762												
						Push the button	⇒	0.000	0.608	0.000												
5	LEDTV5_RefModel_201	RefModel	0130730021	LEDTV5	P1	Assemble the back panel to the main body	O	1.883	2.295	0.000	14.751	1	0	100	14.751	1	0.000	21.340	16.794	13.072	18.108	18.366
						Connect the power for inspection	O	0.926	1.332	0.000												
						Attach the label tape to the main body	O	0.847	0.581	0.000												
						Push the button	⇒	0.000	0.645	0.000												
						Wait	D	0.000	0.000	2.345												
						Check that the parts are properly placed	◇	0.000	3.227	0.000												
						Wait for the back panel part	D	0.000	0.000	0.668												
6	LEDTV6_RefModel_201	RefModel	0130730021	LEDTV6	P1	Wait	D	0.000	1.931	5.842	15.547	5	0	100	3.109	1	0.000	26.587	16.675	13.303	17.239	19.805
						Assemble the screws to the main body	O	5.442	1.740	0.000												
						Push the button	⇒	0.000	0.591	0.000												
7	LEDTV7_RefModel_201	RefModel	0130730021	LEDTV7	P1	Wait	D	0.000	1.259	2.550	14.686	1	0	100	14.686	1	0.000	21.460	16.665	13.994	18.749	19.865
						Assemble the screws to the main body	O	5.100	2.845	0.000												
						Push the button	⇒	0.000	1.216	0.000												
						Inspection	◇	0.000	0.000	1.715												

Figure 18. Line analysis table result.

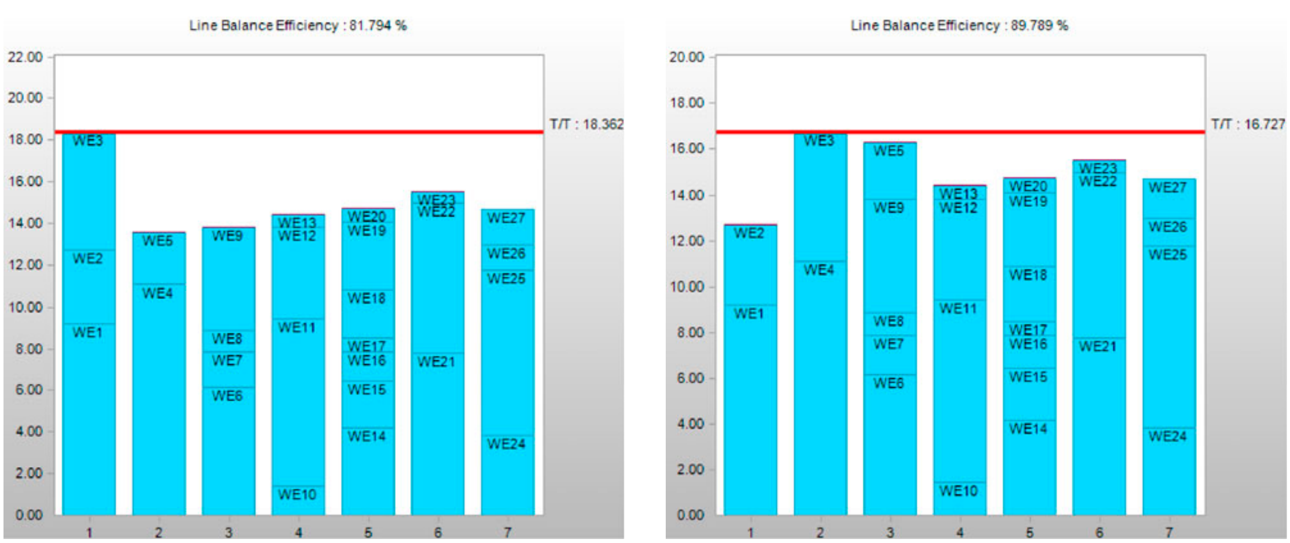


(a) Distributions of cycle times

(b) Time composition by WE types

(c) Time composition by VA types

Figure 19. Interpretation result of workstations.



(a) Before reallocation (b) After reallocation

Figure 20. Work element reallocation result.

TP_j: jth VA type
n: Number of work elements in W_i
T_{ij}: Time of the TP_j of the W_i
TU_{ijk}: Value in a column of TP_k of jth work elements of W_i

To improve an inefficient line balance, work elements of the dominant workstation need to be reallocated to other workstations that are idle or have some spare time. Reallocation assessment supports this activity by determining the time composition of work elements of every workstation using a cumulative bar chart (see Figure 9) constructed by Function (11). A user selects a work element on the chart and allocates it to the other workstation. Then, the modified line balance efficiency is updated and displayed.

(11) Function for the time composition by work elements in all workstations
W_i: ith workstation
T_{ij}: Sum of values in columns of 'VA', 'BVA', and 'NVA' of jth work elements of W_i

4. Implementation

4.1 *Implemented system*

The proposed framework for the continuous performance improvement of manned assembly lines has been implemented based on C++ language in a Visual Studio environment and libraries for the video playback and chart display. Workstation analysis, the first system function, is designed by the three components shown in Figure 11. Users manipulate the video playback controller to analyse a work video and define specific information to complete the workstation analysis table. The analysis result presentation component visualises the defined workstation analysis table using charts so that users can understand performance on various analysis levels of the workstation.

Line analysis, the second function, is composed of the three components shown in Figure 12. Users verify work processes in an assembly line presented in the line analysis table, which are then visualised to represent performance of the line via the analysis result presentation tool. The reallocation assessment entails reallocation of workload and an evaluation of redesigned work processes.

4.2 *Performance improvement example*

In order to examine real-world applications of this study, this paper examined a Korean LED television assembly line consisting of seven workstations. The work-recorded video is obtained from the assembly line, and the analysis data of the video are generated by field engineers. For the explanation of the workstation analysis result, this paper uses one workstation of the assembly line as an example. Figure 13 represents the workstation analysis table result, which is obtained by the analysis of the work video of the example workstation into operation cycles, work elements, unit motions and basic human motions based on MODAPTS. The table is interpreted for four analysis levels (*worker, operation cycle, work element* and *unit motion*) as follows: (1) The analysis of work elements (see Figure 14) represents the most time consuming work elements ('assemble the back panel to the main body', 'check that the parts are properly placed' and 'wait') and WE types ('operation', 'delay,' and 'inspection'). It indicates that the worker consumed time to perform work elements for 'delay' and 'inspection' as much as for 'operation'. (2) Analysis of unit motions (see Figure 15) depicts the time composition by work elements or WE type. For example, 'assemble the back panel to the main body' defined as 'BVA' for 'transportation' consumed about half of the entire time. (3) Analysis of operation cycles (see Figure 16) represents the time distribution of each work element, such as 'assemble the back panel to the main body' that has an operation time of approximately 5.8 s as maximum, 4.4 s as minimum, and between 4.8 and 5.3 s as the deviation. (4) Analysis of workers (see Figure 17) pertains to the time composition of the entire operation of workers in the same workstation by work elements, WE type, VA type or waste type. The analysis can identify that, for example, the workers of the workstation have similar operation time, but the first worker spends more time for 'NVA' than the second worker.

The line analysis table result of the example assembly line in Figure 18 represents the performance of every workstation based on the workstation analysis results. The table is interpreted for the last analysis level (*workstation*) as follows: (5) Analysis of workstations depicts the cycle time distribution and the time composition of workstations by WE type and VA type as shown in Figure 19. It indicates that the second left workstation has the most consistent cycle time (see Figure 19(a)) and that the second right workstation has the largest inefficiency by delay (see Figure 19(b) and (c)).

For better performance of the example assembly line, work elements that are identified by the line analysis can be reallocated into other workstations via reallocation assessment as shown in Figure 20. As a result of the reallocation, the line balance efficiency of the line was increased to 89.8% from 81.8%, and the takt time was reduced to 16.7 s from 18.4 s. Therefore, engineers can suggest the improved process design by using the system.

5. Conclusion

This paper presents a framework that consists of two functions (*workstation analysis* and *line analysis*) to achieve the continuous performance improvement of manned assembly lines for major appliances. It presents a five-level decomposition model to represent a structure of manned assembly lines and examines issues on each analysis level. The paper categorises the analysis levels into two system functions to support the key activities for the continuous performance improvement of manned assembly lines, and proposes analysis tables for each function. Thus, the two system functions fully support the analysis issues. The framework analyses the processes of each analysis level and interprets the results in order to identify sources of inefficiency. A Korean assembly line for LED televisions is used as an example to test the framework's efficacy.

In conclusion, the proposed framework covers all levels of work processes in manned assembly lines. It provides performance improvement processes for work from a lower level to an upper level by minimising inefficiency, and has been verified via implementation of the framework in the manufacturing operations of an electronics company. Future research can address the application of a variant approach to the generation of the assembly process for a manned assembly line. Workstation analysis results are stored in a database, and engineers employ the existing analysis results of the storage to design the assembly process of a manned assembly line for a new product. In this manner, it is possible to define the assembly process of the new assembly line and verify the performance of a designed assembly process.

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