PRODUCTION PLANNING & CONTROL
THE MANAGEMENT OF OPERATIONS

Production Planning and Control

ISSN: 0953-7287 (Print) 1366-5871 (Online) Journal homepage: https://www.tandfonline.com/loi/tppc20

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To cite this article: Rifat Gürcan Özdemir & Zeki Ayağ (2011) An integrated approach to evaluating assembly-line design alternatives with equipment selection, Production Planning and Control, 22:2, 194-206, DOI: 10.1080/09537281003790515

To link to this article: https://doi.org/10.1080/09537281003790515

Production Planning & Control
Vol. 22, No. 2, March 2011, 194–206

An integrated approach to evaluating assembly-line design alternatives with equipment selection

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(*Received 27 June 2006; final version received 15 February 2010*)

The design and implementation of assembly-line systems have been critical issues for companies since the first assembly-line was started at the Ford Highland Plant in 1913. From that time onwards, most companies have met with various problems at the design and implementation stages of assembly-line systems, two of which are the allocation of different work elements to various workstations and the proper equipment selection for workstations. Therefore, in this article, to overcome both the above-mentioned problems, we propose an integrated approach in which a branch and bound algorithm and the analytic hierarchy process (AHP) method are used together. First, the branch and bound algorithm is used to generate a list of assembly-line design alternatives. Then, the generated alternatives are evaluated using the AHP method to determine an optimum solution (the best alternative) at minimum equipment cost. The AHP method is one of the most commonly used multiple-criteria decision-making methods in the literature, and evaluates both qualitative and quantitative evaluation criteria represented in a hierarchical form. The proposed approach is also illustrated on a sample case study.

Keywords: assembly-line design; assembly-line balancing; branch and bound algorithm; multiple-criteria decision making; analytic hierarchy process

1. Introduction

Assembly-line balancing (ALB) and equipment selection for workstations are two of the most important issues in assembly-line systems. When ALB and equipment selection problems are considered simultaneously, the combined problem is known as an assembly-line design (ALD) problem.

The design of an assembly-line is a typical investment decision involving several conflicting objectives such as cycle time (CT), the number of workstations, characteristics of equipment types used in workstations, total investment cost and so on. The equipment types selected for the workstations in an assembly-line specifies not only a part of the total cost (TC), but also the level of reliability and flexibility of the assembly-line. In this decision, all the conflicting objectives should be taken into consideration simultaneously to reach a reliable solution. Finally, a decision maker can make a more accurate and intelligent decision on the selection of the best ALD by considering several objectives rather than any single one. Therefore, the decision-making process should involve multiple objectives in ALD selection.

The multiple-criteria ALD problem (MCALDP) refers to selecting the best ALD in the presence of multiple and usually conflicting objectives. There is much research in the literature devoted to solving the ALD problem (ALDP) with a single objective (i.e. minimising the installation cost of an assembly-line for a given predetermined CT (derived from the required production rate), or minimising the CT (maximising production rate) for a given number of workstations (Johnson 1988, Hoffmann 1992, Scholl and Klein 1997). However, in the literature there are only a few studies concerned with multiple objectives devoted to solving the ALDP. These studies define the design problem without considering equipment selection for the workstations (Malakooti 1991, 1994). However, the ALDP is involved in assigning both the tasks and selected equipment types to the workstations. The ALDP involved in equipment selection and task assignment with multiple objectives are addressed in our study. Also, we show how to combine an optimisation technique (branch and bound) with a decision-making tool (analytic hierarchy process, AHP) representing the subjective judgements of a

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ISSN 0953–7287 print/ISSN 1366–5871 online

DOI: 10.1080/09537281003790515
http://www.informaworld.com

decision maker. The integration of both methods helps the decision maker to play an important role in the final selection (the best ALD alternative), that is an optimal solution for the given parameters.

For this study, the AHP method developed by Saaty (1981) has been selected; this is one of the well-known multiple-criteria decision-making (MCDM) methods, because it consists of a systematic approach based on breaking the decision problem into a hierarchy of interrelated elements. The evaluation of selection criteria is done by using a nine-point scaling system showing that each criterion is related with another. This scaling process is then converted to priority values to compare alternatives. It is a very useful tool in defining the problem structure. The AHP method also integrates the quantitative and qualitative judgements of a decision maker.

Therefore, in this article, we propose an integrated approach in which a branch and bound algorithm and the AHP method are used together. First, the branch and bound algorithm is used to generate a list of ALD alternatives. Then, the generated alternatives are evaluated using the AHP to determine the best alternative at minimum equipment cost. The proposed approach is also illustrated with a sample case study.

2. Literature review

In the literature, most of the studies performed on assembly-line systems have dealt with a simple ALB problem (SALBP) in which assembly tasks are assigned to the workstations subject to precedence relationships between tasks and CT constraints on each workstation's workload. Many exact algorithms have been developed for SALBP; the most popular ones are FABLE by Johnson (1988), EUREKA by Hoffmann (1992) and SALOME by Scholl and Klein (1997). The comprehensive surveys on SALBP solution methods were done by Baybars (1986) and Scholl and Becker (2003). Bukchin and Tzur (2000) also formulated and solved the ALB and equipment selection problems with a single objective (i.e. minimising the total equipment cost of an assembly-line for a given predetermined CT). McMullen and Frazier (1998) and McMullen and Tarasewich (2003) developed a simulated annealing procedure and an ant algorithm for a balancing problem with respect to parallel stations, stochastic task times, mixed-model production and alternative objectives. Pastor *et al.* (2002) considered a mixed-model ALB problem (ALBP) with an additional objective that tries to increase the uniformity of tasks at the stations. Kim *et al.* (2000) proposed a genetic algorithm for two-sided ALBP that arises especially in a production system of trucks. Bukchin and Masin (2004) also considered the problem of combining stations to make larger units (aggregate stations) which are operated by teams of operators. For more detailed classifications and overviews on balancing issues, we referred to, e.g. Baybars (1986), Erel and Sarin (1998), Scholl (1999) and Becker and Scholl (2003).

Ponnambalam *et al.* (2000) proposed a multi-objective genetic algorithm to solve ALBPs. The performance criteria considered are the number of workstations, the line efficiency, the smoothness index before trade and transfer and the smoothness index after trade and transfer. Gamberini *et al.* (2006) developed a new multi-objective heuristic algorithm for solving the stochastic assembly-line re-balancing problem. They integrated a multi-attribute decision-making procedure and a heuristic approach. The proposed methodology does not focus on the balancing of a new line; rather it takes into account the re-balancing of an existing line when some changes in the input parameters occur. Liu and Chen (2002) considered a multi-section electronic ALBP, and they proposed a two-stage approach to resolve this problem. The first stage of their approach involves a multiple objective mixed-integer zero–one programming model in which workstation CT, total operation cost, number of workstations, burn-in duration, burn-in house capacity, buffer size and pallet quantity in use are taken into account. The second stage of the proposed model involves a visual interactive modelling system and the associated human–machine interface for evaluating possible combinations of burn-in duration, burn-in house capacity, buffer size and pallet quantity in use on the achieved assembly system. Malakooti (1991) formulated the multiple-criteria ALBP without buffers. He also solved the multiple-objectives ALDP with buffers, assuming that each workstation has a fixed installation cost, e.g. the same equipment type can be assigned to each workstation (Malakooti 1994). Malakooti and Kumar (1996) considered a multi-objective ALBP with capacity- and cost-oriented objectives and propose a knowledge-based solution approach.

The ALDP involved in equipment selection and task assignment with multiple objectives, to the best of our knowledge, has not been addressed in the literature. Therefore, in this study, we propose an integrated approach in which a branch and bound algorithm and the AHP method are used together to solve the above-mentioned problems under several conflicting objectives. The AHP method requires a list of well-defined criteria to evaluate a set of generated alternatives based on the judgements of the decision maker. Since it was first introduced by Saaty (1981), the AHP method has been widely used in the literature for various MCDM selection problems (i.e. Zahedi 1986, Kodali and Chandra 2001, Ayag 2002, 2005a, 2005b, Scott 2002, Bhagwat and Sharma 2007). In the AHP, a multi-dimensional scaling problem is transformed in a one-dimensional scaling problem (Saaty 1999). The main advantages of AHP are the relative ease in handling multiple criteria, and it can effectively handle both qualitative and quantitative data. The method also elicits preference information from the decision makers in a way which they find easy to understand (Lootsma 1997). In the subsequent sections, we explore the details of our proposed approach for selecting the best ALD configuration.

3. Proposed approach

In this study, an integrated approach is introduced that brings two popular methods together – the branch and bound algorithm and the AHP – to both generate a list of ALD alternatives and evaluate them to find the most satisfying one. As the processes of executing both methods are so time consuming, we developed a computer software using C++ on a PC platform. Especially in the AHP, as the number of criteria increases, the dimension of the problem naturally expands, such as an evaluation matrix with a large number of columns and rows. Figure 1 shows the modules of the developed software and also the interactions and information flows between the modules.

Next, we give more detail of our computer software consisting of various modules as follows: first, the database and user interface module, second, the alternative generation module using the branch and bound algorithm and third, the AHP module including the determination of evaluation.

3.1. *Database and user interface module*

A database and user interface were designed and implemented. This is connected to the user via a data-driven user interface bidirectionally. The database is composed of two major components; the branch and bound algorithm and the AHP. Inputs required for both components are taken through a keyboard from the user to supply the modules with the necessary information. Both the database and the user interface were tested and validated extensively for different cases. Through this user interface, the user not only introduces all required data for the branch and bound and AHP studies to the system, but also gets the results back from them.

3.2. *Alternative generation module*

The MCALDP with equipment selection arises when there are several objectives, each of which affects the equipment selection in a different way. The entire problem can be divided into two subproblems as follows: (1) the equipment selection connected to the line balancing and (2) the selection of the best ALD from among several alternatives that are generated by solving line balancing and equipment selection problems optimally at minimum equipment cost. The former problem addresses the design issue for a given predetermined CT. Equipment is assigned to

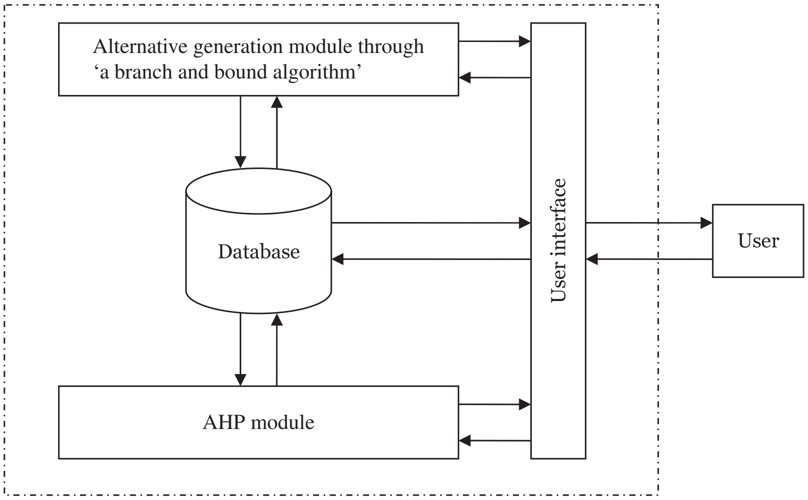

Figure 1. Integrated approach to ALD selection problem.

workstations, while workstations are opened sequentially and a set of tasks that can be performed by the selected equipment is assigned to the corresponding workstations. This problem is solved optimally by a branch and bound algorithm under a set of constraints.

3.2.1. *Problem formulation*

Below, we formulate the ALD with equipment selection problem as a binary integer linear programming (LP) problem. The constraints of the problem are:

1. The CT constraint, which determines the production rate of the line and is thus related to demand expectations.
2. The precedence constraints, which are related to the technological requirements of the assembly job and cannot be further changed.
3. The space constraint, which is related to existing shop floor restrictions.

The problem is then formulated as a binary integer program under the following assumptions: (1) a single product is produced in the assembly line, (2) equipment types and their features are known beforehand, (3) a single equipment type (server) can be assigned to each workstation, (4) the precedence relation between assembly tasks is known, (5) the assembly tasks cannot be further subdivided, (6) the task times are deterministic, but may vary when performed by a different equipment type, (7) a task can be performed at any station of the assembly line, as long as the equipment type assigned to that station can perform the task and the precedence relations are obeyed, (8) the total station time cannot exceed the predetermined CT and (9) material handling, loading and unloading times are included in the task times.

The following variables and parameters are defined so as to formulate the given problem:

t_{kl}	duration of task k when performed by equipment l ($k = 1, \dots, K$, $l = 1, \dots, L$)
ec_l	equipment cost of type l ($l = 1, \dots, L$)
CT	cycle time
SIP_k	set of immediate predecessors of task k ($k = 1, \dots, K$)
$R_{\max}$	maximum number of stages (serially connected workstations)
SC	maximum allowed space requirement for the line
S_l	space requirement of equipment type l ($l = 1, \dots, L$)

$$Y_{lr} = \begin{cases} 1 & \text{if equipment } l \text{ is assigned} \\ & \quad \text{to workstation } r, \\ 0 & \text{otherwise.} \end{cases}$$

$$X_{ldr} = \begin{cases} 1 & \text{if task } k \text{ performed by} \\ & \quad \text{equipment } l \text{ at workstation } r, \\ 0 & \text{otherwise.} \end{cases}$$

Objective function:

$$\min \sum_{l=1}^{L} \sum_{r=1}^{R_{\max}} ec_l Y_{lr}. \tag{1}$$

Subject to:

$$\sum_{l=1}^{L} \sum_{r=1}^{K} r \cdot X_{glr} \le \sum_{l=1}^{L} \sum_{t=1}^{K} t \cdot X_{hlt} \quad \forall g, h \text{ subject to } g \in SIP_h, \tag{2}$$

$$\sum_{l=1}^{L} \sum_{r=1}^{K} X_{klr} = 1 \quad \forall k, \tag{3}$$

$$\sum_{k=1}^{K} t_{kl} X_{klr} \le \mathrm{CT} \cdot Y_{lr} \quad \forall l, r, \tag{4}$$

$$\sum_{l=1}^{\mathrm{L}} Y_{lr} \le 1 \quad \forall r, \tag{5}$$

$$\sum_{r=1}^{R_{\max}} \sum_{l=1}^{L} S_l Y_{lr} \le \mathrm{SC}, \tag{6}$$

$$X_{klr} = \{0, 1\} \quad \forall k, l, r, \tag{7}$$

$$Y_{lr} = \{0, 1\} \quad \forall l, r. \tag{8}$$

The objective function (1) minimises the total equipment cost of the assembly-line for a specific CT. On the other hand, equipment cost includes the following components for each equipment type: procurement and operating costs. Constraint set (2) ensures that if task g is an immediate predecessor of task h, then it cannot be assigned to a station with a higher index than the station to which task h is assigned. Constraint set (3) ensures that each task is performed exactly once. Constraint set (4) represents the relationship between the X_{klr} and the Y_{lr} variables by not allowing any task to be performed on a given piece of equipment in a given station, if this equipment is not assigned to that station. Also, if a given piece of equipment is assigned to a given station, constraint set

(4) specifies the CT requirement. Constraint set (5) represents the requirement of at most one piece of equipment at any station. Each equipment type has a certain space requirement (in space-unit). The designing of an assembly-line also includes a space restriction problem when the new equipment needs to be installed in an existing shop floor which has a certain amount of free space. Constraint (6) ensures that the total space requirement of the equipment assigned to the stations cannot exceed the space capacity, and constraint sets (7) and (8) define the decision variables to be 0–1 binary.

3.2.2. *Alternative generation procedure*

For a predetermined CT, the optimal line configuration can be found for minimising equipment cost. However, it is obvious that when the value of CT in the constraint changes, the equipment cost corresponding to the new optimal line configuration may not be the same. Simply choosing the largest cycle time (LCT) results in the minimum number of stations and thus the minimum equipment cost; however, it obviously results in an unsatisfactory ALD in terms of the production rate. The lower the desired CT, the higher will be the equipment cost. Since the increased number of stations results from a lower CT, it results in an assembly system with a higher space requirement. An ALD with a lower equipment cost is likely to have less reliability and less flexibility, since it is formed with a low reliable and low flexible equipment. As stated above, in the relationships between factors of ALD, each objective conflicts with another, so the decision maker should consider all related criteria to make an informed decision. The decision maker may need to take into account several criteria influencing the equipment selection, and subsequently, the selection of the best ALD, such as space requirement, reliability and flexibility. We also support a list for other definitions and notations used throughout this article as given in Table 1.

Table 1. Notation for alternative generation procedure.

LCT	The largest cycle time selected for a given minimum acceptable production rate
OPS_i	Optimal solution i for a given CT $(i=1,\ldots,N)$
TC_i	Objective function value (total equipment cost) of optimal solution i $(i=1,\ldots,N)$
A_j	ALD alternative j $(j=1,\ldots,M)$ and $M \leq N$
tt_k	Minimum duration of task k, i.e. $tt_k = \min_l\{t_{kl}\}$ $(k=1,\ldots,K)$
SCT	The smallest cycle time that the assembly line can attain, i.e. $\text{SCT} = \max_k\{tt_k\}$
PR_j	Production rate of alternative j $(j=1,\ldots,M)$

In this section, we present a procedure for alternative generation to determine a practical number of alternatives for our problem. All the requested data are entered via a data-driven user interface. First, we need to have a list of the optimal ALD alternatives obtained by an exact solution method. An optimal solution with higher equipment cost can be selected as an alternative as long as it has a lower CT than the other cheaper ALD alternatives. When alternative generation starts with the LCT (derived from a given minimum acceptable production rate), each decrease in CT will result in a higher cost or an equal cost design alternative. Then, the alternative generation procedure determines cost intervals and selects the optimal solution for the best CT in each cost interval as an ALD alternative. Thus, the number of alternatives equals the number of cost intervals. The flow chart for this entire procedure is illustrated in Figure 2.

The optimal solution for a given LCT is selected as the first ALD alternative ($A_1 \Leftarrow \text{OPS}_1$). Then the CT is decreased by one time unit and the next optimal solution is obtained for that CT. If the TC of the current optimal solution is equal to the previous TC value, the last obtained ALD alternative will refer to the current OPS, otherwise the current OPS is selected as the new ALD alternative. The procedure of generating alternatives continues until the optimal solution for the smallest cycle time (SCT) is obtained. After all optimal solutions for CTs (LCT through SCT) are handled, the alternative generation procedure forms a

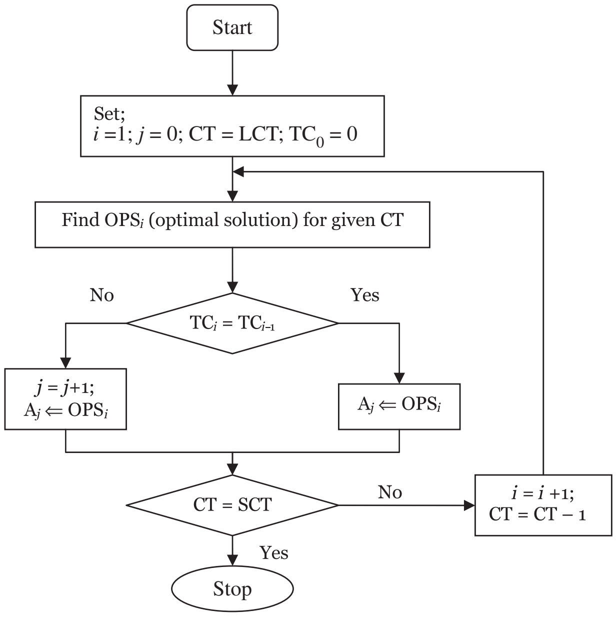

Figure 2. Step-by-step generation of ALD alternatives using the exact algorithm.

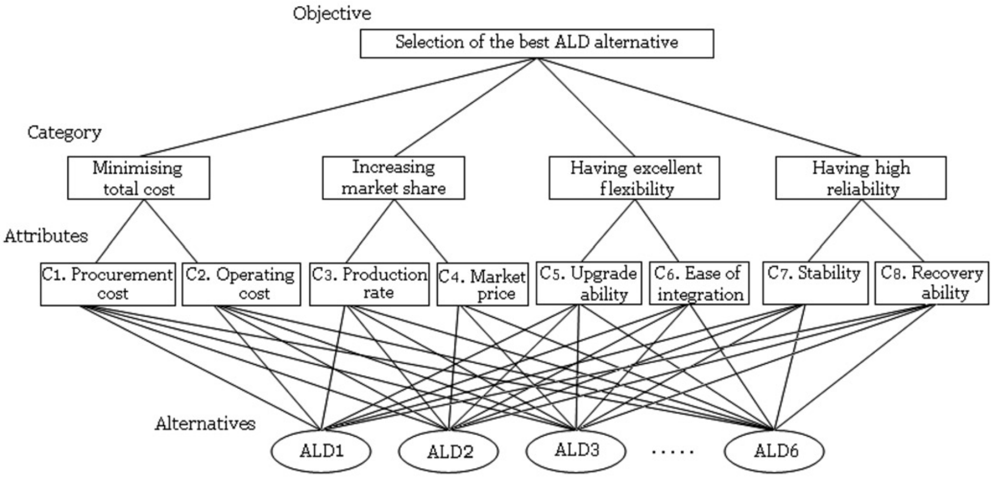

Figure 3. Fundamental-objective hierarchy for the AHP.

list of ALD alternatives, wherein each has a minimum equipment cost and optimal task assignments for the best CT of each cost interval. The alternative generation procedure starts with the LCT and solves the problem of ALB with equipment selection using a branch and bound algorithm. The frontier search branch and bound algorithm utilised in this procedure was previously developed and used for the general equipment selection problem in an ALD stage in the literature (Bukchin and Tzur 2000). The complexity of the algorithm has been reported by the authors as the total number of nodes generated multiplied by the complexity of the work at each node; the latter term was defined as $O(\log_2 T \cdot K \cdot L)$, where T is the maximum number of nodes in the branch and bound tree, K the number of tasks of the assembly job and L the number of pieces of equipment in the problem. Therefore, the overall complexity can be defined as $O(P \cdot (\log_2 T \cdot K \cdot L))$, where P is the total number of nodes generated (the size of the branch and bound). We have to determine a range for CTs that will be considered in the alternative generation procedure, where N denotes the number of CTs between LCT and SCT. We need to solve the above-mentioned algorithm N times to conclude the alternative generation procedure. Thus, the overall complexity of the procedure can be defined as $O(N \cdot P \cdot (\log_2 T \cdot K \cdot L))$.

3.3. *AHP module for the ALD selection*

In the previous section, a procedure has been introduced to generate non-dominated ALD alternatives by using two tangible criteria (i.e. production rate and cost of the selected equipments for workstations). It also eliminates dominated ALD alternatives, while it produces non-dominated alternatives. In this section, we define both tangible and intangible criteria to evaluate the generated non-dominated ALD alternatives in the AHP study, as shown in Figure 3.

As shown in the figure, four categories are defined in the fundamental-objective hierarchy of AHP as follows: *minimising TC, increasing market share, having an excellent flexibility* and *having high reliability*. The first category, minimising TC, consists of two attributes, the *procurement cost* and *operating cost* of equipment types selected for the workstations of the line. Furthermore, the procurement cost of an equipment type includes the installation cost of the material handling system and the space requirement cost. The operating cost is also associated with all kinds of operations carried out for a specified length of period. The second category, increasing market share, consists of two attributes, *production rate* and *market price*. The production rate of an assembly-line, the reciprocal of CT, affects the market share of a company in the long run. The market share is also affected by the price at which the product is sold to customers.

In addition to the above-mentioned four tangible criteria, we have included two intangible categories: *having excellent flexibility* and *having high reliability*. The third category, having excellent flexibility, includes two attributes, *upgrade ability* and *ease of integration*. The last category, having high reliability, also includes two more attributes, *stability* and *recovery ability*. The selecting process of equipment types, of course, is also affected by the judgements of the decision maker on these intangible criteria.

For the user interface, the user only enters all the requested data (i.e. the number of criteria, the matrix of pairwise comparisons for criteria and matrices of

Table 2. Fundamental scale used in pairwise comparison.

1	Represents equal importance for both elements being compared
3	Element A is moderately important as compared with element B
5	Element A is strongly important as compared with element B
7	Element A has demonstrated importance as compared with element B
9	Element A is of extremely important as compared with element B

Source: Saaty (1989).

pairwise comparison of alternatives for each criterion) for the study through a data-driven interactive tool in a user-friendly environment after reading the instructions given in detail on the screen. And then, the following steps can be automatically carried out by using the AHP module: (1) synthesising the pairwise comparison matrix, (2) calculating the priority vector of a criterion, (3) calculating the consistency ratio (CR), (4) calculating$\lambda_{\max}$, (5) calculating the consistency index (CI), (6) selecting the appropriate value of the random consistency index (RCI) and (7) checking the consistency of the pairwise comparison matrix to check whether the decision maker's comparisons were consistent or not.

In the results from the AHP, the user gets the final solution via data-driven user interface. The module ranks all the ALD alternatives by weight and shows the best one with the highest weight to the user. The AHP method was developed by Saaty (1981), and it consists of a systematic approach based on breaking the decision problem into a hierarchy of interrelated elements. The evaluation of selection attributes is done using a scaling system showing that each criterion is interrelated. This scaling process is then converted to priority values to compare alternatives. Table 2 shows this nine-point scale scheme.

4. Model implementation

In the previous section, the AHP-based integrated approach has been presented to evaluate a set of ALD alternatives. In this section, a case study is presented to prove this approach's applicability and validity in order to make it more understandable, especially for the decision makers who are involved in the assembly-line construction process in a company.

4.1. *Numerical example*

This case study was realised in an electronic product supplier to a large-sized company. They make some models of TV sets, and therefore our focus is on a line for the company's single-model TV set in highest demand. The company is contemplating to re-setup the line in the near future, and they want to utilise a more mechanised system than the current system. There are some equipment types available for consideration after having completed a pre-selection process. The summary of the data gathered from the company is given in Table 3. The procurement cost (in €1000), space requirement (in m^2) of each equipment type and the time (in seconds) required to perform every assembly task by each of the equipment types are given in Table 3. Empty elements in the duration table imply that the task cannot be performed by the associated equipment type.

The equipment cost includes two components as previously mentioned; procurement and operating costs. The procurement cost also includes all relevant costs to construct a station along with the equipment type, such as (1) the fixed installation cost of a material handling system per workstation and (2) the space requirement cost related to each equipment type. Beside the procurement costs, the operating cost should be given to conclude the equipment costs. The operating cost regardless of the equipment type selected for a workstation is €50,000 for 1 year's operation time for every station opened in the system. The entire line in the current system fits into a 72 m^2 area (Figure 4). The line should also consist of three separate segments. One of these segments is dedicated to first assembly work elements that must be performed before the heating unit. These first work elements are also considered as assembly tasks that can be performed by the equipment units considered here (i.e. they are given as tasks 1–12 in Table 3). The first segment for tasks 1–12 is currently located in a 32 m^2 area, the second segment, which is dedicated to the heating unit, occupies 16 m^2 and finally, the rest of the total area (24 m^2) is utilised by the third segment of the line dedicated to the inspection and packaging tasks that cannot be performed by the equipment types selected for the workstations of the first segment.

Our primary objective in this case study is to show how the proposed method for an ALDP can be implemented. For this purpose, we have to generate ALD alternatives using the procedure detailed in Section 3.2. The alternative generation procedure requires that the LCTs and SCTs should be determined beforehand. The minimum acceptable production rate is used to determine the LCT. This minimum required production rate is adopted from the existing contracts of the company for the TV set, and the line we focus on is responsible for supplying 120,000 TV set units in 1 year. The line should run at most 120,000 min for the

Table 3. Summary of the assembly process of the TV set.

			Equipment types				
			E1	E2	E3	E4	E5
Task no.	Task description	Preceded by	Task times (s)				
Assembly operations							
1	Placing the front frame on the line	–	15	8	–	12	–
2	Get ready hi-fi to assembly	–	24	12	30	–	9
3	Assemble board to the front frame	1	22	–	32	25	–
4	Assemble chassis sled to the board	3	16	7	–	–	6
5	Assemble hi-fi on to the front frame	1, 2	18	–	35	–	–
6	Assemble control keys to the front frame	1	17	9	–	–	7
7	Get ready tube to assembly	–	20	10	–	–	9
8	Assemble tube to the front frame	1, 7	26	18	32	–	–
9	Assemble chassis to the chassis sled	4, 6, 8	17	9	21	15	10
10	Assemble tube socket on to the tube	8	23	12	–	24	12
11	Assemble degauss bobbin on to the chassis	9	15	–	25	–	15
12	Degauss control	10, 11	8	4	–	9	5
13	Staying on the heating unit[a]	12	–	–	–	–	–
Procurement cost (€ 1000) =			50	50	10	15	25
Space requirement (m^2) =			9	8.5	4	5	2
Inspection and packaging							
14	Focus-screen settings	13	24				
15	Menu settings	13	23				
16	Geometrical settings	14	23				
17	RGB settings	14	21				
18	Format settings	16	16				
19	Assembling the back lid of TV	15, 17, 18	24				
20	Electricity high-tense control	19	15				
21	Solidity control	19	25				
22	Bar-coding	20, 21	19				
23	Putting sticker on TV screen	22	16				
24	Packaging	23	37				

Note: [a]A special task for a TV set assembly process, and there must be a dedicated heating unit in the line as a separate station for this task. It takes 42 s for every unit of TV set to accomplish task 13.

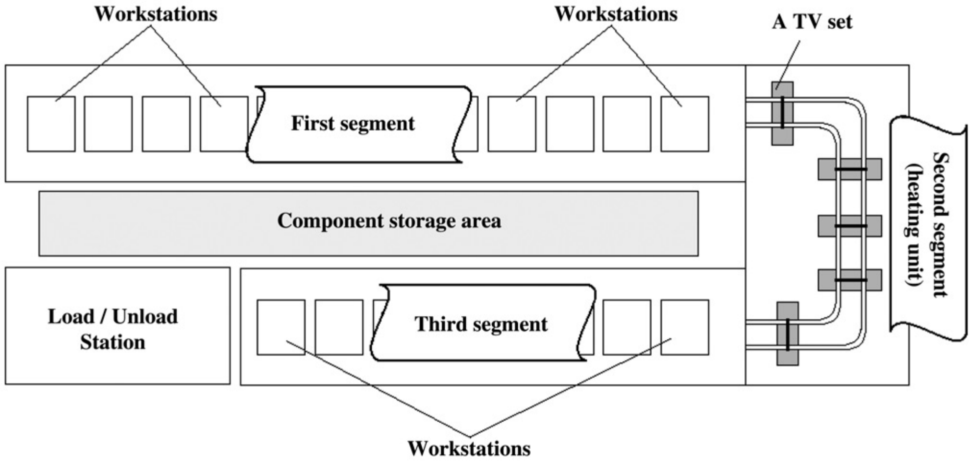

Figure 4. Layout of the assembly line.

Table 4. Generated ALD alternatives for the example problem.

ALD	Equipment and task assignments or tasks 1–12	Task assignments for tasks 14–24
1	E2(8,7,2,1), E1(5,3), E5(12,11,10,9,6,4)	S1(15,14), S2(17,16), S3(20,19,18), S4(22,21), S5(24,23)
2	E2(10,8,7,1), E3(3), E5(12,11,9,6,4,2), E3(5)	S1(15,14), S2(17,16), S3(19,18), S4(21,20), S5(23,22), S6(24)
3	E4(3,1), E2(10,8,7,4), E5(12,11,9,6,2), E3(5)	S1(15,14), S2(17,16), S3(19,18), S4(21,20), S5(23,22), S6(24)
4	E4(3,1), E5(7,6,4,2), E1(8,5), E5(12,11,10,9)	S1(17,14), S2(16,15), S3(19,18), S4(21,20), S5(23,22), S6(24)
5	E4(3,1), E5(7,6,4,2), E1(8,5), E5(12,11,10,9)	S1(14), S2(17,15), S3(18,16), S4(20,19), S5(22,21), S6(23), S7(24)
6	E4(3,1), E5(7,6,4,2), E3(8), E5(12,11,10,9), E3(5)	S1(14), S2(18,16), S3(15), S4(17), S5(20,19), S6(21), S7(23,22), S8(24)

Table 5. ALD alternatives with their tangible criteria (B, C, D) for the AHP study.

ALD	CT (s) A	Procurement cost (€) B	Operating cost (€) C	PR (per minute) $D = 60/\mathrm{A}$	Production capacity (number of TV sets) $E = D \times T^{\mathrm{a}}$	Unit cost (€ per unit) $F = (B + C)/E$
1	55	125,000	400,000	1.09	130,909	4.01
2	52	95,000	500,000	1.15	138,462	4.3
3	47	100,000	500,000	1.28	153,191	3.92
4	46	115,000	500,000	1.30	156,522	3.93
5	44	115,000	550,000	1.36	163,636	4.06
6	42	85,000	650,000	1.43	171,429	4.29

Note: $^{\mathrm{a}}T$ (annual available time) = 120,000 min.

specified period of 1 year, thus the LCT should be 60 s per TV set unit. The SCT is entered in order to stop the alternative generation process. The last alternative solution of ALD is generated for the SCT. In ALBPs the maximum task time represents the SCT that can be attained by the line. Thus, we take 42 s as the SCT since the heating unit will operate at the speed of one TV set unit for every 42 s, which is the maximum task time for all. We input these CTs to the procedure to generate alternatives of ALD. We obtained 18 optimal ALD solutions between the LCTs (60) and the SCTs (42) using the branch and bound algorithm; however, some of them are discarded since they are dominated by others. The alternative generation module returns six ALD alternatives as listed in Tables 4 and 5.

Each alternative ALD in Table 4 involves an optimum balancing solution with a minimum equipment cost for tasks 1–12, and with a minimum number of stations for tasks 14–24. Table 5 shows the cost figures and production performance of each ALD alternative, which are based on the results given in Table 4. For instance, ALD alternative 1 given in Table 4, which was obtained for a given CT of 55 s, has three stations to perform tasks 1–12 and tasks 1, 2, 7 and 8 are performed by equipment type 2 in station 1, tasks 3 and 5 are performed by equipment type 1 in station 2 and equipment type 5 assigned to station 3 performs tasks 4, 6, 9–12. The ALD 1 also has five more workstations to perform tasks 14–24. Cost figures for ALD alternative 1 given in Table 5 have been calculated as follows: procurement cost is related to the selected equipment types and it equals to €125,000 since equipment type 1 (€50,000), equipment type 2 (€50,000) and equipment type 5 (€25,000) are selected for the workstations. The operating cost is the function of the number of stations established in the line, thus the €400,000 cost of operating the ALD 1 for a given period results from the eight workstations, and each costs €50,000.

For a predetermined CT, the optimal line configuration can be found with the objective of minimising equipment cost. However, it is obvious that when CT becomes another decision variable, the objective of minimising equipment cost is no longer sufficient for determining the best line configuration. Simply choosing the LCT that is equal to the total work content minimises the equipment cost; however, it obviously results in an unsatisfactory ALD in terms of production rate. The lower CT results in the fact that total work content should be divided into a greater number stations and/or expensive equipment types that can perform tasks in a shorter time are assigned to the workstations. An optimal solution for the minimum equipment cost for a predetermined CT does not include the decision maker's subjective judgements on factors other than cost. As the AHP provides the

Table 6. Pairwise comparison matrix of the criteria (only upper side shown).

Criteria	C1	C2	C3	C4	C5	C6	C7	C8	Priority vector
C1	1	1	1	5	5	5	7	7	0.273
C2		1	3	3	3	3	3	9	0.245
C3			1	1	3	7	3	5	0.170
C4				1	1	5	1	3	0.097
C5					1	3	1	1	0.067
C6						1	3	1	0.053
C7							1	3	0.060
C8								1	0.035
								$\lambda_{\max}$	8.967
								CI	0.138
								RI	1.41
								CR	$0.098 < 0.1$ Ok.

Table 7. Matrix of paired comparison results of six ALD alternatives with respect to the 1st criteria – procurement cost (C1) (only upper side shown).

ALD	1	2	3	4	5	6	Priority vector
1	1	1	3	5	5	5	0.341
2		1	1	3	3	3	0.223
3			1	1	5	7	0.202
4				1	3	5	0.133
5					1	1	0.053
6						1	0.049
						$\lambda_{\max}$	6.462
						CI	0.092
						RI	1.24
						CR	$0.075 < 0.1$ Ok.

decision maker with other factors (such as ease of integration and upgradeability of equipment types relating to the objective of having excellent flexibility, and stability and recoverability of equipment types which is related to the objective of having high reliability) in ALD selection, the AHP was carried out to find out the best ALD design among the generated alternatives. The data entered into the software are as follows: (1) the number of criteria under four categories (8); (2) the number of the alternatives (6); (3) the matrix of paired comparisons for criteria and (4) the matrix of paired comparison results for alternatives for each criterion. A fundamental scale system by Saaty (1989) given in Table 2 was used to rate both all the ALD alternatives with respect to one criterion at a time and the criteria on each other. All the required calculations were automatically carried out by the AHP module.

Synthesising the pairwise comparison matrix of the criteria is performed by dividing each element of the matrix by its column total. The priority vector of the criteria can be obtained by finding the row averages (Table 6). Similarly, the CI and CR for the matrix of pairwise comparison of criteria for each level was calculated as follows (RCI for the matrix size 8 is 1.41):

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1} = \frac{8.967 - 8}{7} = 0.138,$$

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RCI}} = \frac{0.138}{1.41} = 0.098 < 0.10.$$

For the matrices of pairwise comparisons of alternatives for the seven remaining criteria, the CRs were calculated in the same way, and it was clearly found that they were all less than 10%.

Now, as an example, the CR for the matrix of pairwise comparisons of alternatives for the criterion *procurement cost* (C1) is calculated, and given in Table 7. Similarly, the consistency study for this matrix is given as follows:

$$\lambda_{\max} = 6.462, \quad \mathrm{CI} = (6.462 - 6)/5 = 0.092,$$

$$\mathrm{RCI} = 1.24, \quad \mathrm{CR} = 0.075 < 0.10.$$

Table 8. Final ranking of the ALD alternatives.

ALD	C1 (0.273)	C2 (0.245)	C3 (0.170)	C4 (0.097)	C5 (0.067)	C6 (0.053)	C7 (0.060)	C8 (0.035)	Overall priority vector
1	0.341	0.424	0.357	0.411	0.358	0.391	0.446	0.492	0.386
2	0.223	0.127	0.140	0.278	0.295	0.243	0.227	0.198	0.196
3	0.202	0.201	0.280	0.161	0.198	0.166	0.137	0.131	0.202
4	0.133	0.131	0.097	0.048	0.050	0.116	0.105	0.109	0.109
5	0.053	0.052	0.060	0.062	0.060	0.043	0.050	0.040	0.054
6	0.049	0.065	0.065	0.041	0.039	0.041	0.034	0.031	0.052
CR	0.075	0.081	0.077	0.097	0.076	0.076	0.090	0.083	
								Total	1.000

Note: Overall CI = 0.098.

Based on these calculations, the consistencies of the judgements in all comparison matrices are also acceptable. Finally, the overall priority weight for each ALD alternative was found using the following formula:

$$A^*_{\text{AHP-Score}} = \max_i \sum_{j=1}^{8} w_j \cdot a_{ij}, \quad \text{for } i = 1, 2, 3, 4, 5, 6,$$

where w_i is the relative weight of jth criterion and a_{ij} is the distributive weight of ith alternative for jth criterion.

Also, the overall priority weight of each alternative was calculated. The ALD alternative with the best weight (0.386) was found to be ALD 1, as given in Table 8. In addition, the overall CI was calculated as 0.095 which is smaller than 0.10 (all of the judgements are consistent).

4.2. *Remarks*

In the case study, a set of the ALD alternatives (6) were evaluated in terms of a number of criteria (8) based on the judgements of the assembly-line manager. The AHP results indicate that the manager prefers lower cost alternatives as long as their production rates satisfy the expectations of the company in the near future, without giving any credit to other strategically more important objectives such as increasing market share and having excellent flexibility. This point of view may be because of current habits. The current application of the line configuration by the manager and his crew is as follows: the work elements (or tasks) are assigned to the workstations by only considering precedence constraints (technological orders of performing tasks), next the manager decides on the equipment types to be assigned to the workstations by selecting the minimum cost equipment types that are technologically adequate to perform the work elements of the workstations. After the installation of the selected equipment is completed, the improvement studies start to achieve the target production rate that meets the contracted demands. The improvement studies continue until the line can achieve the target production rate without using overtime. However, it may take 7 months to find the optimal line design, or in the worst case they can never find a line configuration that meets the target demand without the use of overtime.

In our case study, the line manager was satisfied when the line was able to produce the required production rate using regular resources, and he only focused on the manufacturing issues rather than strategic issues that would likely affect the future of the company. If the line manager had focused more on the company's strategies, the proposed approach would have been utilised more efficiently.

Our alternative generation procedure helped the line manager to be sure that he never made inefficient selection since the alternatives were optimal in two ways; that is, they involved both the minimum equipment cost for a given CT and the minimum CT for a given equipment cost. As mentioned earlier, once a CT was entered, the optimal ALD was configured to minimise the cost of equipment selected for the workstations. For some CTs, the same equipment cost was obtained in different assembly-line configurations. Thus, the ALD with the minimum CT was selected among all those with the same equipment cost and taken into consideration in the AHP study as one of the generated alternatives.

In our case study, the line manager was fully convinced that each alternative with different cost was also the best in its cost category in terms of production rate (the reciprocal of CT). This situation made the manager more confident in his judgements.

5. Conclusions and future research

In this article, we proposed an integrated approach to reach the best ALD by considering several conflicting objectives. Therefore, first, the branch and bound algorithm was used to generate a list of ALD alternatives. Then, the alternatives were evaluated by using the AHP. The AHP is a widely preferred method for tackling MCDM problems involving both quantitative and qualitative data, and has successfully been applied to many actual decision situations.

The proposed study contributes to the literature in several ways as follows: AHP decision-making performance is improved by incorporating with an optimal solution technique in alternative generation stage. Whatever AHP turns out as a decision, we can be sure that the preferred alternative is an optimal one for the objective of minimising equipment procurement cost. We propose an approach that integrates AHP and an optimal solution method in a different way than that given in the prior literature (i.e. in literature, AHP is combined with LP or mixed-integer linear programming (MILP) formulations in a way that AHP provides weights as input parameters to mathematical formulations. However, in our proposed approach a MILP formulation is used to provide alternatives as input to AHP). We propose a minor change in equipment selection formulation by considering space requirement as a constraint on the solution of ALD. We develop a new algorithm in which a new version of equipment selection formulation is used iteratively for generating alternatives input to AHP.

In this work, we utilised the branch and bound algorithm to solve the ALBP with equipment selection, and to generate ALD alternatives, each of which consists of different set of equipment assigned to the workstations. The algorithm has an exponential complexity and is capable of solving problems of moderate size. However, the problem considered here is also related to some strategic decisions which might affect the future success of the company.

In our work, we also developed computer software using C++ on a PC platform due to the fact that the processes of both generating ALD alternatives and carrying out the steps of the AHP are quite time consuming for a decision maker or a team of decision makers. Especially in the AHP, as the number of criteria increases, the dimension of the problem naturally expands, involving, for example, an evaluation matrix with a great deal of columns and lines. This means a long and difficult calculation process, especially if all the required calculations are done manually. There is no limitation for using the software, and it can be perfectly used by a decision maker (i.e. manufacturing and assembly-line engineer) who has only a basic knowledge of ALD and MCDM.

In this article, we used the crisp values to make all pairwise comparisons of the AHP. For future studies, to improve the accuracy of the judgements of the decision maker(s), and reduce the vagueness and uncertainty on judgements of the decision maker(s), a fuzzy logic can be introduced in the pairwise comparison of AHP, referred to as fuzzy AHP.

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