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Supply chain optimisation with assembly line balancing

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Supply chain management operates at three levels, strategic, tactical and operational. While the strategic approach generally pertains to the optimisation of network resources such as designing networks, location and determination of the number of facilities, etc., tactical decisions deal with the mid-term, including production levels at all plants, assembly policy, inventory levels and lot sizes, and operational decisions are related to how to make the tactical decisions happen in the short term, such as production planning and scheduling. This paper mainly discusses and explores how to realise the optimisation of strategic and tactical decisions together in the supply chain. Thus, a supply chain network (SCN) design problem is considered as a strategic decision and the assembly line balancing problem is handled as a tactical decision. The aim of this study is to optimise and design the SCN, including manufacturers, assemblers and customers, that minimises the transportation costs for determined periods while balancing the assembly lines in assemblers, which minimises the total fixed costs of stations, simultaneously. A nonlinear mixed-integer model is developed to minimise the total costs and the number of assembly stations while minimising the total fixed costs. For illustrative purposes, a numerical example is given, the results and the scenarios that are obtained under various conditions are discussed, and a sensitivity analysis is performed based on performance measures of the system, such as total cost, number of stations, cycle times and distribution amounts.

Keywords: supply chain design; assembly line balancing; nonlinear mixed-integer programming

1. Introduction

Supply chain management is more than just innovation for the sake of being innovative. It is creating a unique supply chain configuration that drives objectives forward. To get the most from a supply chain, five critical configuration components are needed for consideration under strategic, tactical and operational decisions (Cohen and Roussel 2005):

- operations strategy
- outsourcing strategy
- channel strategy
- customer service strategy
- asset network

While companies have tended to address these components singly, they are now considering a few or all of them. However, considering the configuration components or different decision levels together also forces companies into a number of trade-offs, for example production planning, distribution costs, line balancing, working times, location of facilities, etc. (Schmidt and Wilhelm 2000). Since a supply chain deals with material flows and information flows across the entire chain, from suppliers of original components to final customers, it comprises at least two major integrated domains: production planning, which deals with manufacturing, warehousing and their interfaces, and the distribution and logistics process, which determines how products are retrieved and transported from suppliers to customers (Xiaobo et al. 2007, Tuzkaya and Önüt 2009). In order to realise these major domains, each SCN should identify strategic and tactical decisions that minimise the total costs or maximise the overall value generated.

A supply chain may be considered as an integrated process in which a group of several organisations, such as suppliers, producers, distributors and retailers, work together to acquire raw materials with a view to converting them into end products which they distribute to retailers (Mula et al. 2010). Because there are several organisations,
the efficiency of the supply chain system is influenced by many factors, the most common of which is to determine the location of facilities to be opened and the distribution network strategy in such a way that customer demand can be satisfied at minimum cost or maximum profit (Syarif et al. 2002, Yan et al. 2003, Gen and Syarif 2005, Altiparmak et al. 2006). In addition to the above factor, the production operations should also be decisive factors for the optimisation of SCNs. Assembly line balancing operations, which are one of the decisive factors, are the most common situation in SCNs due to the large number of components. To construct an agile SCN, competent and compatible assembly line processes and supply–distribution processes have to be able to work simultaneously. To deal with these problems, SCN functions should be integrated in a comprehensive framework. This integration should basically be between two main SCN processes such as assembly line balancing and the above transportation functions. This situation can provide visibility, which will lead to greater accuracy, reliability, and customer service levels. At this point, two main aspects gain crucial importance in a SCN. First, companies try to add maximum functions. This situation can provide visibility, which will lead to greater accuracy, reliability, and customer service levels. At this point, two main aspects gain crucial importance in a SCN. First, companies try to add maximum

To optimise the operations of whole areas of the SCN such as line balancing and the fixed costs of opened stations

value by minimising their own transportation costs at each stage of the SCN. Second, companies struggle to optimise the operations of whole areas of the SCN such as line balancing and the fixed costs of opened stations (Tuzkaya and Önüt 2009). Therefore, there is a close linkage between assembly and distribution that necessitates the coordination of assembly and distribution operations in supply chain systems.

In this paper, we present a novel nonlinear mixed-integer mathematical model for a supply chain network consisting of multiple manufacturers that integrates multiple components and multiple assemblers, integrating assembly lines and multiple customers, that have multiple period time horizons with respect to the available capacity restrictions. This model is used to optimise the assignments of tasks to assembly lines to determine optimum stations according to fixed costs and transportation decisions for a multi-echelon supply chain in order to minimise the total transportation cost. Cycle times are determined as a decision variable to connect two problems (SCN and assembly line balancing problems).

The paper is organised as follows. Section 2 reviews the supply chain network design and assembly line balancing problems literature. The proposed nonlinear mixed-integer programming model that minimises the total cost of the overall SCN and minimises the fixed costs of assembly stations and the individual functional units is presented in Section 3. For illustrative purposes, a numerical example is given, the results and the scenarios that are obtained under various conditions are discussed, and a sensitivity analysis is performed in Section 4. Finally, Section 5 concludes the paper and proposes future directions for research.

2. Literature review

Supply chain management has received considerable attention from academicians, researchers and operators during the last several decades. Designing and optimising SCNs is one of the most popular problems in this research field. For that reason, many mathematical and heuristic models have been proposed. Most of these models are related to the transportation/distribution networks with the following considerations (Paksoy and Chang 2010):

- location of the facilities (plants, distribution centres, etc.) to be opened;
- design of the network configuration; and

In addition to the studies mentioned above, a few of the proposed models focus on the integration of specific functions, such as warehousing (Ganeshan 1999, Monthatipkul and Yenradee 2008, Tuzkaya and Önüt 2009), aggregated production planning (Singhvi et al. 2004, Foo et al. 2008) material requirement planning, etc. (Esposito and Passaro 1997, Yan et al. 2003). With respect to modelling, the vast majority of studies use the linear programming-based modelling approach (Martin et al. 1993, Chen and Wang 1997, Kanyalkar and Adil 2005), particularly mixed-integer linear programming models (McDonald and Karimi 1997, Dogan and Goetschalckx 1999, Sakawa et al. 2001, Rizk et al. 2008). Conversely, nonlinear programming is only used in a few studies (Lababidi et al. 2004, Altiparmak et al. 2006). Syarif et al. (2002) defined this kind of problem as being NP-hard because of the combination of multiple choice Knapsack problems with the capacitated location-allocation problem simultaneously. Thus, heuristic and meta-heuristic models have been developed and proposed by Jayaraman and Pirkul (2001), Syarif et al. (2002), Gen and Syarif (2005), and Altiparmak et al. (2009).

In supply chain optimisation models, costs, customer service and inventories are considered mostly for quantitative purposes. According to Mula et al. (2010), regarding costs, the minimisation of costs (Ozdamar and
Yazgac 1997, Azaron et al. 2008), the maximisation of revenues and the maximisation of benefit (Cohen and Lee 1989, Tsai et al. 2008) have been studied, while the maximisation of the service level (Chen and Lee 2004, Torabi and Hassini 2008), the minimisation of backorders (Tuzkaya and Önüt 2009, Paksoy and Chang 2010), flexibility in volume or delivery dates (Sabri and Beamon 2000) or the maximisation of flow have been considered for customer services. The maximisation of safety inventories has also been taken into account.

This section presents a review of mathematical programming models for SCN problems. The analysed papers are given by classification based on the analysis of the supply chain modelling approach and purpose. Conclusions drawn from this section affirm the following.

- Most of the models reviewed consider a supply chain network for production and transportation planning oriented towards the strategic or tactical decision level only. Studies that have integrated the hierarchical structure of the tactical and operative planning levels simultaneously are few in number.
- Because of the complexity of this kind of problem, nonlinear models are less useful than other mathematical models.
- Inventory, backorder and warehouse functions are considered mostly as tactical decision levels.

Due to the above factors, we propose a nonlinear mixed-integer mathematical model that considers strategic and tactical decisions simultaneously. After reviewing past studies, we determined that assembly line balancing problems have not been studied as a tactical decision while designing and optimising a supply chain network. An assembly line consists of several successive workstations, at which assembly operations of a particular product are performed. A task is defined as the smallest portion of an assembly operation. The magnitude of the work content of a workstation is the sum of the completion times of tasks assigned to the workstation. The largest work content of an assembly line is defined as the cycle time of the assembly line (Kara et al. 2009). Assembly lines can be classified in terms of the shape of the line (straight or U-shaped) and also in terms of the number of different products produced on the line (single or mixed) (Gokcen and Agpak 2006). This paper focuses on straight and single assembly lines.

A single-model assembly line is limited to producing one variant (Figure 1) and is mainly used for mass production of one homogeneous product (Hakansson et al. 2008). The problem of assigning tasks to workstations in such a way that certain performance measures are optimised subject to the precedence relationships (Figure 2) among tasks is known as the assembly line balancing (ALB) problem (Kara et al. 2009). Figure 2 shows a precedence graph with n=10 tasks with task times between 2 and 9 (time units). The precedence constraints for task 5, for example, state that its processing requires that tasks 1 and 4 (direct predecessors) and 3 (indirect predecessor) be completed. In other words, task 5 must be completed before its (direct and indirect) successors 6, 8, 9, and 10 can be started (Scholl and Becker 2006).

The simple assembly line balancing problem (SALBP) occurs when stations are equally equipped with respect to workers and machines, alongside a paced line with fixed cycle time and deterministic operation times. Depending on the performance measure considered, three versions of assembly line balancing can be identified (Scholl 1999).

- SALBP-1: Minimise the number of stations J for a given cycle time CT.
- SALBP-2: Minimise the cycle time CT for a given number of stations J.
- SALBP-E: Maximise the line efficiency E or, equivalently, minimise J*CT.

The ALB problem was first formulated mathematically by Salveson (1955). Following this study, many studies on assembly lines, including exact solution methods, heuristics and meta-heuristic approaches, have been reported in the literature to date. Ozcan (2010) reported that reviews of such studies have been given by Baybars (1986), Ghosh and Gagnon (1989), Erel and Sarin (1998), Scholl (1999), Rekick et al. (2002) and more recently by Scholl and

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Figure 1. Straight and single assembly line.

Figure 2. Precedence graph (Scholl and Becker 2006). Reprinted from European Journal of Operational Research, 168, A. Scholl and C. Becker, State of the art exact and heuristic solution procedures for simple assembly line balancing, 666–693, © 2006, with permission from Elsevier.
Becker (2006), Dolgui (2006), and Becker and Scholl (2006). Several techniques have been proposed for the solution of SALB problems with different considerations of task times and configurations (Graves and Lamar 1983, Pinnoi and Wilhelm 1997, Nicosia et al. 2002, Yamada and Matsui 2003, Agpak and Gokcen 2005). According to the studies quoted above, supply chain network design and assembly line balancing problems are always studied separately. However, Che et al. (2009) reported that the operation mechanism of a supply chain is similar to an assembly production line. Hence they attempted to adopt line balancing technology to complete co-operator selection and industry assignment for the cooperation mechanism with the lower delivery delay loss of the supply chain network. But they applied assembly line balancing to the supply chain network problem, therefore they are not considered simultaneously. Che and Chiang (2010) focused on performing supply chain planning for a build-to-order supply chain network. The planning is designed to integrate supplier selection, product assembly, as well as the logistic distribution system of the supply chain in order to meet market demand. They consider three evaluation criteria, namely costs, delivery time, and quality, and a multi-objective optimisation mathematical model is established for build-to-order supply chain planning. However, line balancing is not considered. Sawik (2009) considered the integration of supply, production and distribution in a customer-driven supply chain and proposed mixed-integer programming formulations for the long-term scheduling and coordination of parts manufacturing and supply and finished products assembly. Although the problem considered is how to coordinate the manufacturing and supply of parts and assembly of products such that the total supply chain inventory holding cost and the production line start-up and parts shipping costs are minimised, there is no consideration of assembly line balancing. Xiaobo et al. (2007) consider a supply–assembly–store chain with a produce-to-stock strategy. The chain comprises a set of component suppliers, a mixed-model assembly line (MMAL) with a conveyor linking a set of workstations in series, and a set of finished product storehouses. The paper conducts a modelling and performance analysis in the design stage of the system in the sense of ‘long-term-behaviour’.

According to assembly line managers, the most important goals related to assembly line balancing are the minimisation of the number of workstations or minimisation of the cycle time. In some studies, minimisation of the number of workstations is provided via minimisation of the fixed costs of each station in the assembly line. Askin and Zhou (1997), Amen (2000) and McMullen and Tarasewich (2006) consider cost parameters for stations, workers and equipment in assembly line balancing problem objectives. In the aforementioned objectives, the cycle times and number of stations should be constant and given. However, this situation can change and be complex in some assemblers that deal with a supply chain network. Decision makers cannot ignore supply chain activities while balancing assembly lines, or ignore assembly line balancing while designing a supply chain network for a supply chain that has assemblers. These two main problems are completely interactive. Transportation amount, the capacity of facilities, and changing demand directly affect the cycle time and total stations in assemblers.

To the best of our knowledge, there is no published study dealing with supply chain network design and assembly line balancing problems simultaneously in the literature. Consequently, in this paper, simultaneous optimisation of the supply chain and assembly lines is introduced and characterised. Therefore, the considered problem is a new problem and the problem becomes even more difficult in our case due to the NP-hard structure of the supply chain network and assembly line balancing problems. A nonlinear mixed-integer mathematical model is developed to model and solve the problem. For integration of the two problems, cycle times are transformed into decision variables. The results of computational experiments of the developed model on a set of test problems are reported.

3. Optimisation of supply chain networks with assembly lines
In this section, a nonlinear mixed-integer model is developed to solve the optimisation problem of a supply chain network with assembly lines. First, the problem is described, and the problem assumptions are given. The mathematical formulation of a deterministic version of the problem is then presented.

3.1 Integration of supply chain network design and assembly line balancing
In this section, the optimisation of a supply chain network while balancing the assembly lines is discussed. A typical supply chain network design problem has typical inputs such as a set of customer zones to serve, a set of products to be manufactured and distributed, demand projections for the different customer zones, and information concerning future conditions, costs (e.g., for production and transportation) and resources (e.g., capacities, available
raw materials). Supply chain network design problems deal directly with a set of products to be manufactured or assembled. To consider this relation, we embedded the assembly line balancing problem into a supply chain network design problem. We determined the cycle time ($CT$) as the integration point of these two problems. The cycle time is the time required to complete a given process. In our model, the working time is certain, but the number of products needed to be assembled is variable according to the obtained outputs of the network design problem. Equation (1) shows that the work content of workstation $j$ does not exceed the cycle time of assembler $a$ in period $p$. The cycle times of assembler $a$ in period $p$ are determined by dividing the transported amount from assembler $a$ to all customers $c$ by the working time in period $p$:

$$\sum_{i} t_{i} v_{aijp} \leq CT_{ap} \quad \forall a,j,p$$  \hspace{1cm} (1)$$

$$CT_{ap} = \frac{W_{time}}{\sum_{c} Y_{acp}} \quad \forall a,p$$  \hspace{1cm} (2)$$

Therefore, while the model determines the transported amounts between facilities to satisfy demand, it also balances the stations according to variable cycle times. We determined a fixed cost per period to open a station in the proposed model, therefore our objective is to minimise the transportation costs and minimise the total fixed costs of the stations simultaneously. Therefore, our proposed assembly line balancing problem is entirely different from existing SALB problems due to the simultaneous station and cycle time variability. The basic assumptions of the proposed model are as follows.

- The demand of each customer for a product is deterministic and must be fully satisfied (i.e. no shortages are allowed). The demands and the transported materials are divisible amounts, which is applicable in the case of supply chains of gas or liquid products.
- The flow is only allowed to be transferred between two sequential echelons.
- The capacities of manufacturers and assemblers are limited and are known in advance.
- All parameters are deterministic and known.
- A single model of one product consisting of $i$-1 components is produced on an assembly line.
- The cycle time of each assembler is variable.
- The travel times of operators are ignored.
- No work-in-process inventory is allowed.
- A task cannot be split among two or more stations and all tasks must be processed.
- The precedence relations of the problem are known.
- All stations can process any of the tasks and all have the same associated costs.
- The task process time is independent of the station and, furthermore, they are not sequence dependent.
- Any task can be processed at any station.
- The line is serial, with no feeder or parallel subassembly lines and process times are additive at any station.
- The line is designed for a unique model of a single product.

The first four are standard assumptions for supply chain designs considered in other studies. The remainder of the assumptions, except for the cycle time, are defined by Baybars (1986).

3.2 Mathematical model

The indices, sets, parameters and decision variables used in the mathematical formulations are given as follows.

**Indices**

- $m$ index of manufacturers
- $a$ index of assemblers
- $c$ index of customers
- $p$ index of periods
- $k$ index of components
- $i, r, s$ index of tasks
- $j$ index of workstations
Sets and parameters

- \( M \): number of manufacturers
- \( A \): number of assemblers
- \( C \): number of customers
- \( P \): number of periods
- \( K \): number of components
- \( J \): number of stations (upper bound) which can be estimated from a heuristic procedure
- \( N \): number of tasks
- \( L \): set of tasks that precedes from a task

\((r,s)\in L\) a precedence relationship; \( r \) is an immediate predecessor of \( s \)

- \( t_i \): task time of task \( i \) (time units)
- \( W_{time} \): working time in period \( p \) (time units)
- \( a_{mkp} \): capacity of manufacturer \( m \) for component \( k \) in period \( p \) (units)
- \( b_{ap} \): capacity of assembler \( a \) in period \( p \) (units)
- \( u_{cp} \): demand of customer \( c \) in period \( p \) (units)
- \( C_{map} \): unit cost of shipping from manufacturer \( m \) to assembler \( a \) in period \( p \) (monetary units/distance \( \text{units*units} \))
- \( C_{acp} \): unit cost of shipping from assembler \( a \) to customer \( c \) in period \( p \) (monetary units/distance \( \text{units*units} \))
- \( D_{ma} \): distance between manufacturer \( m \) and assembler \( a \) (distance units)
- \( D_{ac} \): distance between assembler \( a \) and customer \( c \) (distance units)
- \( O \): fixed cost to open a station in the assembly line in all periods (monetary units, MU)

Variables

- \( X_{makp} \): amount shipped from manufacturer \( m \) to assembler \( a \) for component \( k \) in period \( p \)
- \( Y_{acp} \): amount shipped from assembler \( a \) to customer \( c \) in period \( p \)
- \( V_{aijp} \): 1, if task \( i \) is assigned to workstation \( j \) for assembler \( a \) in period \( p \); 0, otherwise
- \( Z_{ajp} \): 1, if there is any task assigned to workstation \( j \) for assembler \( a \) in period \( p \); 0, otherwise
- \( CT_{ap} \): cycle time for assembler \( a \) in period \( p \)

Objective function:

\[
Z_1 = \sum_{m}^{M} \sum_{a}^{A} \sum_{k}^{K} \sum_{p}^{P} X_{makp} \cdot D_{ma} \cdot C_{map} + \sum_{a}^{A} \sum_{c}^{C} \sum_{p}^{P} Y_{acp} \cdot D_{ac} \cdot C_{acp} + 
\]

\[
Z_2 = \sum_{a}^{A} \sum_{j}^{J} \sum_{p}^{P} Z_{ajp} \cdot O
\]

The objective function consists of two main parts \((Z_1, Z_2)\). The first (Equation (3)) tries to minimise the total shipping costs of the first and second stages in the supply chain network during any period. The second part (Equation (4)) minimises the total fixed costs for operating the stations in the assemblers during any period. Therefore, \( Z_2 \) finds a feasible assignment of tasks that minimises the sum of fixed costs.

Constraints:

\[
\sum_{a}^{A} X_{makp} \leq a_{mkp} \quad \forall m,k,p
\]

\[
\sum_{c}^{C} Y_{acp} \leq b_{ap} \quad \forall a,p
\]
Constraints (5) and (6) limit the total quantity of components shipped from the manufacturer to assemblers, and the total quantity of product shipped from the assembler to customers cannot exceed the capacity of that manufacturer and assembler during any period, respectively. Constraint (7) gives the satisfaction of customer demand for all products during any period. Constraint (8) guarantees that the total component quantity that is shipped from manufacturers to the assembler must be equal to the total shipped product quantity from that assembler to customers that is able to satisfy the demand during any period. Constraint (9) is the assignment constraint and ensures that each task is assigned to exactly one station in all assemblers during any period. Constraint (10) is known as the precedence constraint and provides the precedence relationship by assigning task \( r \) as an immediate predecessor of task \( s \) in all assemblers during any period. Constraint (11) is the cycle time constraint and prevents the cycle time being exceeded for a station in all assemblers during any period. Constraint (12) shows that the cycle time in all periods is equal to the total working time in all periods divided by the total product quantity that is needed to be produced in all periods for all assemblers. Constraint (13) states that station \( j \) is used if any task is assigned to it in all assemblers during any period. Constraint (14) imposes the non-negativity restriction on decision variables \( (X_{makp}, Y_{acp}, CT_{ap}) \). Constraint (15) is the non-divisibility constraint and states that any task can be assigned to a station as a whole or not.

4. Computational experiments
In this section we present a numerical example to illustrate the model. The application of the model is performed for a hypothetical data set. The considered supply chain includes four manufacturers, two assemblers and four customers. While determining the transportation amounts between manufacturers, assemblers and customers, the model also attempts to balance the assembly lines in assemblers at the same time. The supply chain network is shown in Figure 3.
Manufacturers produce seven different components and send them to assemblers to produce end-products. After completion of the assemble processes in assemblers, end-products are transported to customers. As stated above, the cycle time is defined as a decision variable. The model tries to find how many products will be transported from assemblers to customers in addition to balancing the assembly lines according to the cycle time under fixed costs.

Seven different components are assembled in the assembler according to the precedence graph shown in Figure 4. The figure also shows the precedence graph with \( N = 8 \) tasks with task times between 2 and 6 (minutes). Relevant data are given below. Table 1 gives the distances and unit transportation costs, and Tables 2 and 3 give the capacities and demands of each facility.

We apply our proposed model to a supply chain network using the single model eight-task assembly line balancing problem shown in Figure 4. A period is 3 months (12 weeks), and 5 days are worked in one week with 8 working hours in one day. Therefore, \( W_{\text{time}} = 12 \times 5 \times 8 \times 60 = 28,800 \text{ min} \). Data related to the example are \( M = 4 \), \( C = 4 \), \( P = 2 \), \( K = 7 \), \( J = 6 \), \( N = 8 \), \( O = 0.3 \text{ MU} \) and \( W_{\text{time}} = 28,800 \text{ minutes} \), and the set of tasks that precedes from a task (L) are \((1\rightarrow2), (1\rightarrow4), (2\rightarrow5), (4\rightarrow5), (3\rightarrow6), (5\rightarrow7), (6\rightarrow7), (6\rightarrow8) \) and \((7\rightarrow8)\). The proposed model is solved via LINGO, which uses branch-and-bound algorithm (B and B) 11.0 on a Pentium IV PC running at 3.06 GHz (3 GB RAM) and takes 2 minutes 20 seconds. The results obtained are shown in Table 4.

According to the results obtained by LINGO, all customers are satisfied. The total transportation cost is 4,065,360.40 MU. In total, 12 stations are opened with \( 12 \times 0.3 = 3.6 \text{ MU} \) during any period. The model balanced all assembly stations in assemblers to satisfy customers in all periods. According to the optimal results, the cycle times are determined as follows:

\[
C_{11} = \frac{W_{\text{time}}}{(Y_{111} + Y_{121} + Y_{131} + Y_{141})} = \frac{28,800}{2720} \approx 10.58 \text{ min}
\]

\[
C_{12} = \frac{W_{\text{time}}}{(Y_{112} + Y_{122} + Y_{132} + Y_{142})} = \frac{28,800}{3600} = 8 \text{ min}
\]

\[
C_{21} = \frac{W_{\text{time}}}{(Y_{211} + Y_{221} + Y_{231} + Y_{241})} = \frac{28,800}{2800} = 10.28 \text{ min}
\]

\[
C_{22} = \frac{W_{\text{time}}}{(Y_{212} + Y_{222} + Y_{232} + Y_{242})} = \frac{28,800}{1760} = 16.36 \text{ min}
\]

The optimal distribution between assemblers and customers is shown in Figure 5.

All assembly lines are balanced in assemblers during any period. As can be seen from Figure 5, \( 1360 + 1360 = 2720 \) units are transported from the first assembler to customers in the first period. To assemble these units, the optimal line balance consists of three work stations with a cycle time of 10.58 minutes for the first period in the first assembler. The work contents of the workstations for the optimal solution are given in Table 5.
In the second period, assembler 1 assembled 3600 units of product while balancing the line with four workstations with a cycle time of 8 minutes. Table 6 gives the work contents of the first assembler in the second period.

Figure 6 shows the straight line layout for the optimal solution in assembler 1 for the first and second periods.

At assembler 2, in total 2800 units of product are assembled and transported to customers. The optimal line balance consists of three workstations with a cycle time of 10.28 minutes for the first period. This line is assembled with no idle time. The work contents of the workstations for the optimal solution are given in Table 7 for the second assembler in the first period.

In the second period, the second assembler assembled 1760 units of product while balancing the line with two workstations with a cycle time of 16.36 minutes. Table 8 gives the work contents of the second assembler in the second period.

Figure 7 shows the straight line layout for the optimal solution in assembler 2 for the first and second periods.
Table 4. Optimal results for the test problem.

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<td>2521</td>
<td>1</td>
</tr>
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<td>4252</td>
<td>1760</td>
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<td>1</td>
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<td>1</td>
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<td>2800</td>
<td>141</td>
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<td>2651</td>
<td>1</td>
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<td>4262</td>
<td>1760</td>
<td>142</td>
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<td>1641</td>
<td>1</td>
<td>2622</td>
<td>1</td>
</tr>
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<td>3131</td>
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<td>4271</td>
<td>2800</td>
<td>152</td>
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<td>1</td>
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<td>4272</td>
<td>1760</td>
<td>211</td>
<td>1</td>
<td>1741</td>
<td>1</td>
<td>2722</td>
<td>1</td>
</tr>
<tr>
<td>3151</td>
<td>2720</td>
<td>1111</td>
<td>1360</td>
<td>212</td>
<td>1</td>
<td>1752</td>
<td>1</td>
<td>2851</td>
<td>1</td>
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<tr>
<td>3161</td>
<td>2720</td>
<td>1112</td>
<td>1360</td>
<td>221</td>
<td>1</td>
<td>1841</td>
<td>1</td>
<td>2822</td>
<td>1</td>
</tr>
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<td>3171</td>
<td>2720</td>
<td>1131</td>
<td>1360</td>
<td>222</td>
<td>1</td>
<td>1852</td>
<td>1</td>
<td></td>
<td></td>
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<tr>
<td>4211</td>
<td>2800</td>
<td>1132</td>
<td>1040</td>
<td>251</td>
<td>1</td>
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<td>1</td>
<td>2111</td>
<td>1</td>
</tr>
<tr>
<td>4212</td>
<td>1760</td>
<td>1142</td>
<td>1200</td>
<td>1111</td>
<td>1</td>
<td>2112</td>
<td>1</td>
<td></td>
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</tr>
<tr>
<td>4221</td>
<td>2800</td>
<td>221</td>
<td>1440</td>
<td>1112</td>
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<td>2211</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5. Distribution amounts between assemblers and customers during any period.

Table 5. Optimal line balancing for the first assembler in the first period.

<table>
<thead>
<tr>
<th>Workstation</th>
<th>Tasks assigned</th>
<th>Workstation time (min)</th>
<th>Idle time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1–2–4</td>
<td>10</td>
<td>0.58</td>
</tr>
<tr>
<td>2</td>
<td>3–5</td>
<td>10</td>
<td>0.58</td>
</tr>
<tr>
<td>3</td>
<td>6–7–8</td>
<td>10</td>
<td>0.58</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>30</td>
<td>1.74</td>
</tr>
</tbody>
</table>

Table 6. Optimal line balancing for the first assembler in the second period.

<table>
<thead>
<tr>
<th>Workstation</th>
<th>Tasks assigned</th>
<th>Workstation time (min)</th>
<th>Idle time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1–4</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>3–6</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>2–5</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>7–8</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>30</td>
<td>2</td>
</tr>
</tbody>
</table>

Figure 6. Balanced assembly diagram of assembler 1 in the first and second periods.
Figure 8 shows the determined cycle time, total assigned stations and idle time of each assembler during any period. According to Figure 8, the maximum cycle time (16.36) and minimum stations are calculated in assembler 2 in period 2. The best balanced assembly line is assembler 2 in period 1 with three stations and 0.84 minutes idle time. The minimum cycle time and maximum stations are obtained in assembler 1 in period 2.

The solution to the test problem shows that the proposed model is valid and useful for optimising supply chain design and assembly lines simultaneously. While all customers are satisfied with the design of the whole supply chain, assembly lines in assemblers are also balanced.

4.1 Scenario analyses for managerial insights

The integration of assembly line balancing and supply chain network design is the key point of this paper. This is handled by defining the cycle time ($C_{op}$) as a decision variable. As mentioned above, the cycle time of each assembler during any period can be calculated by dividing the total transported amount between assembler and customers by the total working time of each period. Therefore, the demand is a decisive factor. When the results are examined, it is seen that each customer’s demand affects both the supply chain network and assembly lines directly. By changing
The demand limitations of customers, different scenarios can be applied to the model to examine the relations and trade-offs among model variables. Also, scenario analyses are considered in this section to examine the affects of cycle time with respect to different daily working hours on product distribution amounts from assemblers to customers. Therefore, the solution of the model without any scenario (the current solution) and the results of the six main scenarios and 56 sub-scenarios are compared in this section. Because the main objective of assembly lines is balancing and minimising the stations, the total fixed costs are not considered in the scenarios. Only the number of opened stations, cycle times, assigned tasks and total transportation costs are considered in the scenarios. The main scenarios are listed in Table 9.

### Table 9. Main scenarios.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Decreasing and increasing five times the customers’ demand from 5 to 25% during any period</td>
</tr>
<tr>
<td>B</td>
<td>Decreasing and increasing five times the demands of the first customer from 5 to 25% during any period while the other customer demands are constant</td>
</tr>
<tr>
<td>C</td>
<td>Decreasing and increasing five times the demands of the second customer from 5 to 25% during any period while the other customer demands are constant</td>
</tr>
<tr>
<td>D</td>
<td>Decreasing and increasing five times the demands of the third customer from 5 to 25% during any period while the other customer demands are constant</td>
</tr>
<tr>
<td>E</td>
<td>Decreasing and increasing five times the demands of the fourth customer from 5 to 25% during any period while the other customer demands are constant</td>
</tr>
<tr>
<td>F</td>
<td>Decreasing and increasing totally six times the daily working hours of each period from 7 to 10 hours while the other parameters are constant</td>
</tr>
</tbody>
</table>

The first scenario (A) considered is the effect of decreasing and increasing demand for products on the performance measures (total transportation cost, total stations, assigned tasks, CPU time and cycle time). Scenario A, which is applied to reflect real-life problems, is given in Table 10 together with its sub-scenarios.

### Table 10. Scenario A with sub-scenarios for decreased and increased demand.

<table>
<thead>
<tr>
<th>Scenario A</th>
<th>Change (%)</th>
<th>Customer 1</th>
<th>Customer 2</th>
<th>Customer 3</th>
<th>Customer 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Period 1</td>
<td>Period 2</td>
<td>Period 1</td>
<td>Period 2</td>
</tr>
<tr>
<td>1</td>
<td>–25</td>
<td>1020</td>
<td>1020</td>
<td>1080</td>
<td>960</td>
</tr>
<tr>
<td>2</td>
<td>–20</td>
<td>1088</td>
<td>1088</td>
<td>1152</td>
<td>1024</td>
</tr>
<tr>
<td>3</td>
<td>–15</td>
<td>1156</td>
<td>1156</td>
<td>1224</td>
<td>1088</td>
</tr>
<tr>
<td>4</td>
<td>–10</td>
<td>1224</td>
<td>1224</td>
<td>1296</td>
<td>1152</td>
</tr>
<tr>
<td>5</td>
<td>–5</td>
<td>1292</td>
<td>1292</td>
<td>1368</td>
<td>1216</td>
</tr>
<tr>
<td>Current</td>
<td>0</td>
<td>1360</td>
<td>1360</td>
<td>1440</td>
<td>1280</td>
</tr>
<tr>
<td>6</td>
<td>+5</td>
<td>1428</td>
<td>1428</td>
<td>1512</td>
<td>1344</td>
</tr>
<tr>
<td>7</td>
<td>+10</td>
<td>1496</td>
<td>1496</td>
<td>1584</td>
<td>1408</td>
</tr>
<tr>
<td>8</td>
<td>+15</td>
<td>1564</td>
<td>1564</td>
<td>1656</td>
<td>1472</td>
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<tr>
<td>9</td>
<td>+20</td>
<td>1632</td>
<td>1632</td>
<td>1728</td>
<td>1536</td>
</tr>
<tr>
<td>10</td>
<td>+25</td>
<td>1700</td>
<td>1700</td>
<td>1800</td>
<td>1600</td>
</tr>
</tbody>
</table>

The demand limitations of customers, different scenarios can be applied to the model to examine the relations and trade-offs among model variables. Also, scenario analyses are considered in this section to examine the effects of cycle time with respect to different daily working hours on product distribution amounts from assemblers to customers. Therefore, the solution of the model without any scenario (the current solution) and the results of the six main scenarios and 56 sub-scenarios are compared in this section. Because the main objective of assembly lines is balancing and minimising the stations, the total fixed costs are not considered in the scenarios. Only the number of opened stations, cycle times, assigned tasks and total transportation costs are considered in the scenarios. The main scenarios are listed in Table 9.

The first scenario (A) considered is the effect of decreasing and increasing demand for products on the performance measures (total transportation cost, total stations, assigned tasks, CPU time and cycle time). Scenario A, which is applied to reflect real-life problems, is given in Table 10 together with its sub-scenarios.

We present the results of Scenario A with its sub-scenarios in Table 11 and Figures 9–11. Demands are modified from –25 to +25% on current demand to examine the changes in total transportation costs, assigned stations and CPU time (Table 11). Figures 11(a) and (b) give the cycle time and assigned tasks of each assembler during any period according to the sub-scenarios of Scenario A.

The results presented in Table 11 and Figures 9 and 10 have the following implications. First, the increase in demand results in a linear increase in transportation costs (Figure 9). The main reason for this result is that the increasing demand of customers will result in the transportation of many more products from manufacturers to customers via assemblers. The same situation is also valid and observed for opened stations. The increasing demand systematically decreases the cycle time in each assembler while $W_{time}$ is constant. Therefore, the model selected to open new assembly stations to satisfy each customer under diminishing cycle times. The total opened stations is between 11 and 16 (Figure 9). According to Scenario A, if the decision maker encounters a 25% decrease in demand,
he/she should reduce the total opened stations from 12 (current) to 11. In contrast, if there is a 25% increase in demand, the decision maker has to open four more stations to meet the demand. Due to the complexity of the model, the CPU time is also increasing while demand is increasing. In particular, there is a remarkable gap in CPU time between the eighth and ninth sub-scenarios of Scenario A.

The amount of products outgoing from each assembler changes in each sub-scenario of Scenario A due to the nature of the supply chain design problem. Therefore, changes in stations in each assembler are also variable (Figure 10). As a result, in these scenario clusters, while the demand is increasing, total transportation costs, total opened stations and CPU time also increase linearly.

All assigned tasks, stations and cycle times of each assembler during any period are shown in Figures 10(a) and (b). Cycle times are changed between 7 and 25.26 minutes (Figures 11(a) and (b)). The minimum station number is two and the maximum is five in all sub-scenarios of Scenario A.
While the total demand is increasing, the cycle time distribution narrows, as seen in sub-scenarios 8–10 (Figure 12). The main reason for this situation is that the transportation amounts between assemblers and customers have a balancing distribution while the demands are increasing. For example, while the transportation quantities between assemblers and customers are 1260, 2880, 2880, and 1140, respectively, in sub-scenario 1, these quantities are 3300, 3953, 3600, and 2746, respectively, in sub-scenario 2. Therefore, the change in the cycle time distribution, which is associated with the transportation amounts between assemblers and customers, is an expected situation while the percentage of demands increases.

In this section, the simultaneous effect of all customer demand changes on transportation cost, opened stations and assigned tasks is investigated. Scenarios B, C, D and E examine the effect of each customer demand...
increase on total transportation costs and assigned stations while the other customer demands are constant (Tables 12 and 13).

Tables 12 and 13 show that increasing each customer’s demand while the other customers’ demands remain constant results in an increase in the total transportation cost. This relationship is linear, as shown in Figure 13. A 25% increase in demand of customers 1, 2, 3 and 4 during any period increases the total transportation costs by 6.19, 6.25, 6.74 and 5.81%, respectively, with respect to the current situation. This shows that if the decision maker is obliged to reduce or give up part of the demand, he/she should use his/her preference for customer 3, or customer 4 should be chosen if the decision maker wishes to minimise the total cost while increasing demand.

Table 12. Results for Scenarios B and C for transportation costs, stations and CPU time.

<table>
<thead>
<tr>
<th>Scenario B</th>
<th>Change (%)</th>
<th>Period 1</th>
<th>Period 2</th>
<th>Cost</th>
<th>Total stations</th>
<th>CPU time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-25</td>
<td>1020</td>
<td>1020</td>
<td>3,813,420.10</td>
<td>4+3+3+3: 13</td>
<td>109</td>
</tr>
<tr>
<td>2</td>
<td>-20</td>
<td>1088</td>
<td>1088</td>
<td>3,863,807.50</td>
<td>3+4+4+4: 15</td>
<td>16</td>
</tr>
<tr>
<td>3</td>
<td>-15</td>
<td>1156</td>
<td>1156</td>
<td>3,914,194.40</td>
<td>3+3+3+3: 12</td>
<td>121</td>
</tr>
<tr>
<td>4</td>
<td>-10</td>
<td>1224</td>
<td>1224</td>
<td>3,964,584.40</td>
<td>2+4+4+2: 12</td>
<td>37</td>
</tr>
<tr>
<td>5</td>
<td>-5</td>
<td>1292</td>
<td>1292</td>
<td>4,014,972.40</td>
<td>3+4+3+2: 12</td>
<td>215</td>
</tr>
<tr>
<td>Current</td>
<td>0</td>
<td>1360</td>
<td>1360</td>
<td>4,065,560.40</td>
<td>3+4+3+2: 12</td>
<td>140</td>
</tr>
<tr>
<td>6</td>
<td>+5</td>
<td>1428</td>
<td>1428</td>
<td>4,115,748.40</td>
<td>3+3+3+3: 12</td>
<td>117</td>
</tr>
<tr>
<td>7</td>
<td>+10</td>
<td>1496</td>
<td>1496</td>
<td>4,166,136.40</td>
<td>3+3+3+3: 12</td>
<td>407</td>
</tr>
<tr>
<td>8</td>
<td>+15</td>
<td>1564</td>
<td>1564</td>
<td>4,216,524.40</td>
<td>3+3+3+3: 12</td>
<td>215</td>
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<tr>
<td>9</td>
<td>+20</td>
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<td>1632</td>
<td>4,266,912.10</td>
<td>4+3+3+3: 13</td>
<td>321</td>
</tr>
<tr>
<td>10</td>
<td>+25</td>
<td>1700</td>
<td>1700</td>
<td>4,317,299.80</td>
<td>3+4+4+3: 14</td>
<td>244</td>
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</table>

Customer 2 demand

<table>
<thead>
<tr>
<th>Scenario C</th>
<th>Change (%)</th>
<th>Period 1</th>
<th>Period 2</th>
<th>Cost</th>
<th>Total stations</th>
<th>CPU time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-25</td>
<td>1080</td>
<td>960</td>
<td>3,811,320.40</td>
<td>2+3+4+3: 12</td>
<td>82</td>
</tr>
<tr>
<td>2</td>
<td>-20</td>
<td>1152</td>
<td>1024</td>
<td>3,862,128.40</td>
<td>3+3+3+3: 12</td>
<td>117</td>
</tr>
<tr>
<td>3</td>
<td>-15</td>
<td>1224</td>
<td>1088</td>
<td>3,912,936.40</td>
<td>3+3+3+3: 12</td>
<td>67</td>
</tr>
<tr>
<td>4</td>
<td>-10</td>
<td>1296</td>
<td>1152</td>
<td>3,963,744.40</td>
<td>3+3+3+3: 12</td>
<td>77</td>
</tr>
<tr>
<td>5</td>
<td>-5</td>
<td>1368</td>
<td>1216</td>
<td>4,014,552.40</td>
<td>3+4+3+2: 12</td>
<td>188</td>
</tr>
<tr>
<td>Current</td>
<td>0</td>
<td>1440</td>
<td>1280</td>
<td>4,065,360.40</td>
<td>3+4+3+2: 12</td>
<td>140</td>
</tr>
<tr>
<td>6</td>
<td>+5</td>
<td>1512</td>
<td>1344</td>
<td>4,116,168.40</td>
<td>3+3+3+3: 12</td>
<td>62</td>
</tr>
<tr>
<td>7</td>
<td>+10</td>
<td>1584</td>
<td>1408</td>
<td>4,166,976.10</td>
<td>3+3+4+3: 13</td>
<td>481</td>
</tr>
<tr>
<td>8</td>
<td>+15</td>
<td>1656</td>
<td>1472</td>
<td>4,217,784.10</td>
<td>3+3+4+3: 13</td>
<td>737</td>
</tr>
<tr>
<td>9</td>
<td>+20</td>
<td>1728</td>
<td>1536</td>
<td>4,268,592.20</td>
<td>3+5+4+4: 16</td>
<td>16</td>
</tr>
<tr>
<td>10</td>
<td>+25</td>
<td>1800</td>
<td>1600</td>
<td>4,319,400.10</td>
<td>3+3+4+3: 13</td>
<td>195</td>
</tr>
</tbody>
</table>
The mean values of opened stations in each of Scenarios B, C, D and E are 12.64, 12.64, 12.73 and 11.91 (Tables 12 and 13), respectively. From this, scenario sets B, C, D and E show that changing the third customer’s demand mostly leads to open assemble stations, then comes customer 2, 1 and 4, respectively. There is an additional managerial insight that can be obtained from Tables 12 and 13 – the frequency of change of the stations in all assemblers during any period. Figures 14–17 show these frequencies according to different customer demand.

### Table 13. Results for Scenarios D and E for transportation costs, stations and CPU time.

<table>
<thead>
<tr>
<th>Scenario D</th>
<th>Change (%)</th>
<th>Customer 3 demand</th>
<th>Cost</th>
<th>Total stations</th>
<th>CPU time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>–25</td>
<td>1020</td>
<td>3,791,220.10</td>
<td>2+4+4+2: 13</td>
<td>13</td>
</tr>
<tr>
<td>2</td>
<td>–20</td>
<td>1088</td>
<td>3,846,047.80</td>
<td>2+4+5+3: 14</td>
<td>27</td>
</tr>
<tr>
<td>3</td>
<td>–15</td>
<td>1156</td>
<td>3,900,876.10</td>
<td>3+3+3+4: 13</td>
<td>95</td>
</tr>
<tr>
<td>4</td>
<td>–10</td>
<td>1224</td>
<td>3,955,704.40</td>
<td>3+3+3+3: 12</td>
<td>95</td>
</tr>
<tr>
<td>5</td>
<td>–5</td>
<td>1292</td>
<td>4,010,532.40</td>
<td>3+3+3+3: 12</td>
<td>255</td>
</tr>
<tr>
<td>Current</td>
<td>0</td>
<td>1360</td>
<td>4,065,360.40</td>
<td>3+4+3+2: 12</td>
<td>140</td>
</tr>
<tr>
<td>6</td>
<td>+5</td>
<td>1428</td>
<td>4,120,188.40</td>
<td>3+3+3+3: 12</td>
<td>534</td>
</tr>
<tr>
<td>7</td>
<td>+10</td>
<td>1496</td>
<td>4,175,016.40</td>
<td>3+3+3+3: 12</td>
<td>873</td>
</tr>
<tr>
<td>8</td>
<td>+15</td>
<td>1564</td>
<td>4,229,844.40</td>
<td>3+3+3+3: 12</td>
<td>284</td>
</tr>
<tr>
<td>9</td>
<td>+20</td>
<td>1632</td>
<td>4,284,672.10</td>
<td>3+3+3+3: 13</td>
<td>132</td>
</tr>
<tr>
<td>10</td>
<td>+25</td>
<td>1700</td>
<td>4,339,499.50</td>
<td>2+4+5+4: 15</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scenario E</th>
<th>Change (%)</th>
<th>Customer 4 demand</th>
<th>Cost</th>
<th>Total stations</th>
<th>CPU time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>–25</td>
<td>1020</td>
<td>3,829,140.40</td>
<td>2+4+4+2: 12</td>
<td>19</td>
</tr>
<tr>
<td>2</td>
<td>–20</td>
<td>1088</td>
<td>3,876,384.40</td>
<td>3+3+3+3: 12</td>
<td>86</td>
</tr>
<tr>
<td>3</td>
<td>–15</td>
<td>1156</td>
<td>3,923,627.80</td>
<td>2+4+4+4: 14</td>
<td>14</td>
</tr>
<tr>
<td>4</td>
<td>–10</td>
<td>1224</td>
<td>3,970,872.40</td>
<td>3+3+3+3: 12</td>
<td>85</td>
</tr>
<tr>
<td>5</td>
<td>–5</td>
<td>1292</td>
<td>4,018,116.40</td>
<td>3+3+3+3: 12</td>
<td>198</td>
</tr>
<tr>
<td>Current</td>
<td>0</td>
<td>1360</td>
<td>4,065,360.40</td>
<td>3+4+3+2: 12</td>
<td>140</td>
</tr>
<tr>
<td>6</td>
<td>+5</td>
<td>1428</td>
<td>4,112,603.50</td>
<td>3+6+4+2: 15</td>
<td>17</td>
</tr>
<tr>
<td>7</td>
<td>+10</td>
<td>1496</td>
<td>4,159,848.10</td>
<td>3+3+4+3: 13</td>
<td>234</td>
</tr>
<tr>
<td>8</td>
<td>+15</td>
<td>1564</td>
<td>4,207,092.10</td>
<td>3+3+4+3: 13</td>
<td>543</td>
</tr>
<tr>
<td>9</td>
<td>+20</td>
<td>1632</td>
<td>4,254,336.10</td>
<td>3+3+4+3: 13</td>
<td>557</td>
</tr>
<tr>
<td>10</td>
<td>+25</td>
<td>1700</td>
<td>4,301,580.10</td>
<td>3+3+4+3: 13</td>
<td>783</td>
</tr>
</tbody>
</table>

![Figure 13. Changes in total cost according to Scenarios B, C, D and E.](image-url)
It can be seen that there are variations in the number of stations when the demand changes between \(-25\%\) and \(+5\%\) in each assembler for all scenarios. In contrast, there is a more or less regular station distribution for changes in demand between \(+5\%\) and \(+15\%\). A possible reason for this situation may be the balanced distribution between the assembler and the customers after a \(+5\%\) increase in demand. Increasing the first customer’s demand (Scenario B)
results in most variability in the station number. Then changes, respectively, in the third, fourth and second customer’s demand has most effect. In other words, it can be stated that the variability or uncertainty in the first customer’s demand leads to the maximum variability in the stations. While Scenario B changes stations 19 times, Scenario D changes 17 times, Scenario E 16 times and Scenario C 10 times.

Scenario F provides managerial insight for decision makers if the daily working time changes. Inferences for decision makers concerning cycle times and transported quantities between facilities can be obtained. Figure 18 shows the transported amount between assemblers and customers during any period when the daily working time changes from 7 to 10 hours step by step. According to these scenarios, increasing the daily working hours also increases the product amount outgoing from the first assembler in the second period and from the second assembler in the first period. Therefore, if the decision maker increases the daily working time, assembly line balancing in assembler 1 in period 2 and assembler 2 in period 1 becomes difficult. Also, increasing the daily working time prevents a balanced distribution between assemblers and customers. With a 7-hour working period, the distribution is 2210 and 3150 units. When it is set at 10 hours, it oscillates between 1360 and 4160 units. Therefore, the decision maker has to keep the working hours low to distribute the total load to the assembler equally under the same demand.

The above situation concerning transported amounts between assemblers and customers can also be seen in Figure 19. This figure shows the calculated cycle times in the assembler during any period according to different daily working times. Although the daily working time increases, it should be noted that the cycle times are distributed differently. The reason for this situation can be explain by referring to Figure 18. Because of the increased transported amounts from assembler 1 in period 2 and assembler 2 in period 1 to customers, the cycle times are short in these assemblers during those times. In contrast, the cycle times increase in assembler 1 in period 1 and assembler 2 in period 2 because of the decreasing transported amounts between these assemblers and customers during those times.
5. Conclusion

This paper addresses an important issue concerning the application of strategic and tactical decisions in supply chain management. The main objective of this paper is to introduce and characterise the problem of integrating supply chain network design and assembly line balancing problems. For this purpose, in this paper, a novel nonlinear mixed-integer programming formulation is developed to model and solve the problem. The proposed mathematical model considers the optimum distribution network while balancing the assembly lines in each assembler simultaneously. An illustrative example problem is solved using the proposed approach, and a numerical experiment is conducted to demonstrate the efficiency of the proposed approach. The model results were compared using different scenarios. Sensitivity analyses were then performed to measure the sensitivity of the model results for different parameter values. The presented study is almost the first study of the simultaneous optimisation of the supply chain network and assembly lines.

This study shows that assembly lines and supply chain networks should be optimised simultaneously. The contributions of this paper are as follows. (i) It describes a modelling approach for incorporating straight assembly line balancing into existing design methods for supply chain networks. (ii) It presents a nonlinear mixed-integer programming formulation for supply chain network design, which, in contrast to all existing studies, minimises total costs composed of transportation and assembly line balancing. (iii) It presents extensive computational analyses that capture the trade-off between various performance measures. The results of the computational experiments on hypothetical instances yielded the following.

- Increasing or decreasing demand directly affects the amounts transported between facilities and the opened assembly stations. A 25% increase in demand results in a 24.97% increase in the overall cost and a 33% increase in the total number of opened stations. In contrast, a reduction of 25% in demand causes a reduction of 25.03% in the overall cost and a decrease of 8.33% in the total number of opened stations.
- A 25% increase in demand of customers 1, 2, 3 and 4 during any period increases the total transportation costs by 6.19%, 6.25%, 6.74% and 5.81%, respectively. This shows that if the decision maker is obliged to reduce or give up part of the demand, he/she should use his/her preference for customer 3, or, in contrast, customer 4 should be chosen if the decision maker wishes to minimise the total cost while increasing demand.
- A similar situation is observed for the assembly lines. The mean values for opened stations are 12.64, 12.64, 12.73 and 11.91, respectively, while the demands of each customer change. From this viewpoint, the scenario sets show that changing the third customer’s demand leads to most open assembly stations, followed by customer 2, 1 and 4, respectively.
- The proposed model also shows that increasing the daily working time in assemblers leads to an unbalanced distribution between assemblers and customers. Therefore, the decision maker has to maintain short working hours to distribute the total load to the assemblers equally under the same demand.
- Finally, increasing the daily working time by 42% (from 7 to 10 hours) also results in an increase of 72.42% in the total cycle times in assemblers.

Overall, the model developed here can help a manager quickly respond to customers’ needs, and determine the correct policies to order raw materials, deliver finished goods, balance the assembly lines and efficiently manage their operations. As a result, an organisation can benefit economically by effectively managing the supply chain.

Supply chain network design and assembly line balancing problems are defined as being NP-hard, indicating that the number of computational steps increases exponentially with the number of inputs. Thus, the integration of these problems becomes even more difficult in our case. Therefore, efficient heuristic and meta-heuristic approaches such as genetic algorithms, tabu search, and ant colony optimisation need to be developed to solve the problem. Several extensions are possible for the integration of assembly lines and supply chain networks. Different types of assembly lines such as U-shaped, parallel and disassembly lines, and also different types of networks such as reverse, closed-loop and decentralised supply chains, should be studied simultaneously to observe the different interactions. Also, studying multiple-criteria decision-making techniques such as the goal programming and fuzzy goal programming approaches may be good subjects for considering more strategic and tactical decisions. Finally, applying the planning models to real case studies is suggested for future work.
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References


