AUTOMATION LEVEL OPTIMIZATION FOR AN AUTOMOBILE ASSEMBLY LINE

(BİR OTOMOBİL MONTAJ HATTI İÇİN OTOMASYON SEVİYESİ OPTİMİZASYONU)

by

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LIST OF SYMBOLS

SALB	: Simple Assembly Line Balancing
ALB	: Assembly Line Balancing
B&B	: Branch and Bound
GGA	: Group Genetic Algorithm
PROMETHEE	: Preference Ranking Organisation Method for Enrichment Evaluations
rALB-I	: type I Robotic Assembly Line Balancing
rALB-II	: type II Robotic Assembly Line Balancing
ALDP	: Assembly Line Design Problem
OEMs	: Original Equipment Manufacturers
OEE	: Overall Equipment Efficiency
KPIs	: Key Performance Indicators
FMEA	: Failure Modes and Effect Analyses
BIW	: Body in White
CPH	: Car per Hour
EMS	: Electro Motor System
WIP	: Work in Process

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ABSTRACT

The automotive sector has been one of the industries with greatest importance throughout the history. The assembly is an essential part of the manufacturing of most products. The design of assembly lines plays a crucial role for the success of manufacturing since it affects both the manufacturing cost and productivity. The economic importance of assembly as a manufacturing process has led to extensive efforts for improving the efficiency and cost effectiveness of assembly operations. A common way of assembling complex products such as automobiles is to use advanced assembly systems, which consists of multiple workstations. At each workstation, a group of parts are added to the semi-finished product that moves from one workstation to the next either by a conveyor, by a track, by a device or manually until the finished product is obtained. Assembly lines can be manually operated, automated, or of mixed design.

When an automobile manufacturer develops a new car model, this requires new production lines to be constructed or the existing lines to be reconfigured. Especially, the body shop needs to be entirely rebuilt when a new car model is developed unless it is a face-lift model that necessitates only a few minor changes in an existing model. Even for a face-lift, the changes in the body shop are relatively more difficult to make than in the other shops.

Automotive manufacturing is a complicated process that requires automation to some extent. Automated assembly has low labour cost but very high capital costs because of the expensive automation equipment required, while manual assembly is characterized by high labour costs and low capital costs. The level of automation is a strategic decision that should be made during the initial phase of the car manufacturing project that starts with the conceptual design. Automation level is calculated considering the amount of tasks performed using automation versus using labour in the workstations of the assembly line.

The problem considered in this thesis is to determine the optimum level of automation for an automobile assembly line where tasks can be performed either manually or using robots. The aim is to determine the level of automation which minimizes the total cost of investment, labour and operations while meeting overall requirements.

We propose a mixed integer programming model in order to determine the types of workstations to be used in the assembly line as well as task assignments to workstations. The constraints of the model are defined based on a real case regarding the assembly of a commercial vehicle in an automobile manufacturing plant in Turkey. A numerical experimentation is done to see the effects of unit labor cost and annual demand on the optimum line configuration and automation level.

RÉSUMÉ

L’industrie automobile est un secteur de grande importance qui a été largement reconnue. La production de nombreux produits est faite en utilisant la ligne d'assemblage. Le design de la ligne d’assemblage a un rôle vital dans le succès de la production comme il a des effets directs sur le coût de production et la productivité. En général, il faut qu’on utilise les lignes de montage pour produire des produits complexes tels que les voitures. La ligne de montage est composée de plusieurs stations de travail. Dans chaque station, un certain nombre de pièces est ajouté à un produit semi-fini jusqu’à l'obtention du produit fini.

Quand les constructeurs d’automobiles développent un nouveau modèle de voiture, il est nécessaire d'établir une nouvelle ligne de production ou changer la configuration de la ligne de production existante. En particulier, la ligne de production doit être presque entièrement reconstruite, sauf s’il suffit de faire un maquillage (face –lift), c.à.d. faire un nouveau visage avec quelques petits changements dans le modèle actuel du véhicule.

La production d’automobile est un processus compliqué qui nécessite l’automation à un certain niveau. Les lignes de montage automatisées ont des coûts de main d‘œuvre bas mais des coûts d'investissement très élevés car ils nécessitent des équipements très chers comme les robots, tandis que les lignes de montages manuels ont des coûts de main d’œuvre élevés mais des coûts d’investissement bas. Déterminer le niveau d'automatisation est une décision stratégique, qui doit être faite dans la phase initiale du projet de production du véhicule. Le niveau d'automatisation de la ligne de montage est calculé en considérant la quantité de travail faite dans les stations automatisées versus celle qui est faite manuellement.

Dans cette étude, on considère le problème d’optimisation du niveau d’automation d’une ligne de montage pour les automobiles où les opérations peuvent être faites par les robots et aussi manuellement. Le but est de déterminer le niveau d’automation qui

répond à tous les besoins du système en minimisant le coût total qui consiste au coût d'investissement, coût de main d'œuvre et coût d'opérations.

On propose un modèle de programmation à nombre entiers mixte pour déterminer les types de stations à utiliser dans la ligne de montage et l'allocation des taches aux stations. Les contraintes du modèle sont définies en considérant un cas réel concernant le montage d'un véhicule commercial dans une usine de production d'automobile en Turquie. Une expérimentation numérique est faite pour voir les effets du coût de main d'œuvre et de la demande annuelle sur la configuration optimale de la ligne de montage et le niveau optimal d'automation.

ÖZET

Tarih boyunca otomotiv sektörü, büyük öneme sahip bir sektör olmuştur. Genel olarak otomobil gibi karmaşık ürünler üretibilmenin yolu ileri montaj sistemleri kullanmaktır. Montaj hattı tasarımı imalatın başarısında hayati öneme sahiptir, çünkü hem üretimin maliyetini hem de üretkenliğini doğrudan etkiler. Bir ürün üretebilmek için genelde çok istasyonlu bir montaj hattı kurmak gereklidir. Montaj hattında, her bir istasyonda bir takım parçalar yarı-bitmiş ürüne ilave edilir ve bitmiş ürün elde edilene kadar ya bir konveyör sistemiyle ya bir kızakla ya da bir cihazla yarı ürünler bir istasyondan diğerine hareket ettirilir. Montaj hatları manuel, otomatik veya yarı-otomatik olarak tasarlanabilir.

Otomobil üreticisi yeni bir araç modeli geliştireceği zaman, ya yeni bir üretim hattı kurmak gereklidir ya da mevcut üretim hattı yeniden konfigüre edilmelidir. Özellikle aracın gövdesinin üretimi için, üretim hattı neredeyse tamamen yeniden inşa edilmelidir. Otomotiv sektöründe makyaj (face-lift) model diye adlandırılan, mevcut modellerdeki bazı küçük değişikliklerle yeni bir yüzle aracın müşteriye sunulması bile olsa gövde hattı yeniden düzenlenmelidir. Özellikle gövde hatlarında değişiklik yapmak diğer bölümlere nispeten daha zordur.

Otomobil üretimi belli bir seviyeye kadar otomasyon gerektiren karmaşık bir süreçtir. Otomatize edilmiş montaj hattı, yüksek yatırım maliyetine sahiptir çünkü pahalı otomasyon ekipmanları gerektirir. Manuel montaj ise yüksek işçilik maliyetine sahipken düşük ekipman maliyeti gerektirir. Otomasyon seviyesini belirlemek stratejik bir karar olup, ilk yatırım aşamasında, hatta araç üretiminin konsept tasarımı aşamasında verilmesi gereken bir karardır. Montaj hattının otomasyon seviyesi, manuel istasyonlarda yapılan iş miktarına kıyasla robotik istasyonlarda yapılan iş miktarı dikkate alınarak hesaplanır.

Bu tezde, görevlerin manuel ya da robotlarla yapılabildiği bir otomobil montaj hattı için otomasyon seviyesinin en iyilenmesi problemi dikkate alınmıştır. Amaç, yatırım, işçilik ve işletim maliyetlerinden oluşan toplam maliyeti en küçükleyen ve tüm sistem gereklerini sağlayan bir otomasyon seviyesini belirlemektir.

Montaj hattını oluşturacak istasyon tiplerini ve hangi istasyona hangi görevlerin atanması gerektiğini belirlemek için bir tamsayılı programlama modeli önerilmiştir. Modelin kısıtları, Türkiye'deki bir otomobil üreticisinin gövde üretim hatlarında üretilen ticari bir modele ilişkin gerçek veriler temel alınarak tanımlanmıştır. Sayısal deneyler yapılarak, işçilik maliyeti ve yıllık talep miktarındaki değişimlerin optimum otomasyon seviyesi ve hat konfigürasyonu üzerine etkileri incelenmiştir.

1. INTRODUCTION

Historically, the assembly has played a crucial role in the manufacturing of most systems and products. Assembly lines are special flow-line production systems which are typical in the industrial production of standardized commodities in large quantities (Scholl, 1999). An assembly line is a set of sequential workstations typically connected by a continuous material handling system (Nahmias, 1997).

In order to manufacture a product, it is generally preferred to construct an assembly line, which is done by either using simple technological lines or using advanced technological lines. A common way of assembling complex products such as automobiles is to use advanced assembly systems. In these assembly systems there is a manufacturing process that consists of multiple workstations. At each workstation, a group of parts is added to the semi-finished product that moves from one workstation to the next either by a conveyor, a track, a device or manually until the finished product is obtained.

The design of assembly lines plays a crucial role for the success of manufacturing since it affects both the manufacturing cost and productivity. The economic importance of assembly as a manufacturing process leads to extensive efforts for improving the efficiency and cost effectiveness of the assembly operations. Assembly lines can be manually operated, automated, or of mixed design. There are situations where manual labor is preferred to automation such as when the demand is fluctuating or the product is technically too complicated to assemble using robots or the product life cycle is too short and a fast market launch is required for customized products (Lindström & Winroth, 2010). On the other hand, automation may be preferred to labor for better productivity and better product quality reasons or it may even be a necessity such as when the tasks need to be performed in hazardous environments where manual labor cannot be used due to safety issues or the tasks are too difficult to be performed by humans such as the tasks requiring fine accuracy or heavy loads (Gorlach & Wessel, 2008).

Manual assembly is characterized by high labor costs and low capital costs, while automated assembly has low labor cost but very high capital costs because of the expensive automation equipment required (Rubinovitz et al., 1993). The recent advances in robot technology have led to higher productivity at lower cost, which increased the attractiveness of the automation by manufacturers, yet highly automated manufacturing systems are not necessarily the best in terms of cost, productivity and quality criteria. On the other hand, highly manual systems may not be the best either since the low level of automation may cause poor quality and productivity. Thus, when the assembly tasks for a product can be done using both labor and automated systems such as robots, it is critical to determine the best automation level for the assembly line, which meets the desired productivity and quality levels at the lowest cost (Gorlach & Wessel, 2007). The automation level of an assembly line is calculated considering the amount of tasks performed using automation versus using labor in the workstations of the assembly line. Hence, the problem of determining automation level is in fact an assembly line design problem where the decisions regarding the workstation types and task assignments to workstations are made.

In this thesis, we propose a mixed integer programming formulation to determine the optimum configuration of the assembly line for a vehicle produced by an automotive manufacturer in Turkey. Particularly, given the list of tasks required to complete the assembly of the vehicle or a sub-module of the vehicle and a set of alternative equipment or workstation types available to perform these tasks, the proposed model determines the optimal decisions on which workstation type to select and which tasks to assign to them so as to meet the target production volume at the minimum total system cost. Through a numerical study, the effects of changing the demand for the car and labor cost on the optimum automation level of the line (i.e. the percentage of tasks done in robotic stations) are investigated.

Despite the practical importance of equipment selection and task assignments in assembly systems, only few studies can be found in the literature specifically focusing on the automation level optimization. Our study contributes to the literature by proposing an optimization model to determine the optimum automation level for an automobile assembly line and by solving it using real data from an automobile manufacturer.

This thesis is organized into six chapters as follows:
In Chapter 2, the literature review on robotic assembly line balancing and equipment selection is presented.

In Chapter 3, fundamentals of assembly line balancing are introduced. Moreover, the aims and classification of assembly line balancing are described in this chapter.

In Chapter 4, the basic concepts and terminologies used in assembly line design problems are introduced. Moreover, the phases in automotive manufacturing and methodologies are described in this chapter.

In Chapter 5, the problem is described in details and the proposed mixed integer programming model is presented.

In Chapter 6, the proposed model is illustrated using real data from an automobile manufacturer. A numerical experimentation is done in order to investigate the effects of demand and labor cost on the optimum automation level.

In Chapter 7, conclusions are provided and further work is suggested.

2. LITERATURE SURVEY

Assembly line production systems are utilized to manufacture a large variety of products. As the products have different characteristics, different production systems are necessary to produce them, and therefore, a wide range of assembly line balancing models have been studied. Since its discovery, the assembly line balancing problem has been attracting the interest of many researchers. The main classifications used in the literature are according to the number of the products, the variation of the task times and the operation mode, i.e. paced and unpaced.

The task times are classified as deterministic and stochastic. The automated manufacturing systems or assembly lines which are equipped with flexible machines or robots are assumed to work at a constant speed, so for robotic lines the deterministic task time assumption fits well. Some other times, the variations in the task times may be significant and this may affect the performance of the system; in this case, the task times are modeled as stochastic. When the lines are operated manually, the variations of the task times are expected due to the skills and motivations of the employees. Moreover, due to the learning effects or successive improvements of the production process, the variations in task times may occur.

Most studies on assembly line design consider the *simple assembly line balancing* (SALB) problem where the common assumptions are that the task times are deterministic and independent of the equipment or workstation they are assigned to, and a task can be assigned to any workstation as long as the technological precedence relations are not violated and the cycle time is not exceeded by assigning the task to the workstation (Mitsuo et al., 2008). In the SALB problem, the objective is to assign tasks to workstations such that the cycle time is minimized for a given number of workstations or the number of workstations is minimized for a given cycle time.

There are a few studies in the literature that consider the assembly line design problem where there are alternative equipment/workstation types available for performing the tasks. Clearly, the task times and costs vary depending on the equipment selected. Robotic assembly lines are such assembly lines where a different robot, tooling, and assembly equipment may be used at each workstation. Because different types of robots may have different capabilities, specializations and performance times for each task, the assignment of different robots or equipment to workstations restricts the tasks to be assigned at a given workstation, i.e. a given workstation may not be equipped to perform all tasks as opposed to the SALB problem.

The work presented by Graves and Lamar (1983) is among the earliest studies on assembly line design where each workstation in the line is chosen among a set of non-identical workstation candidates and the tasks are assigned to these workstations such that a pre-specified production rate is achieved at the minimum system cost. An integer programming procedure is proposed to solve the problem.

In a later study, Graves and Redfield (1987) solve the problem of equipment selection and task assignment for multi-product assembly systems. The system costs include the fixed capital costs for the equipment to use in workstations and the variable workstation operating costs. In order to find the least-cost assembly design, they use a graph representation where each candidate workstation corresponds to an arc and solve the shortest path problem on this graph.

Falkenauer (1997) proposes a genetic algorithm for ALB with 'resource dependant tasks times' algorithm based on a Group Genetic Algorithm (GGA) and a Branch & Bound (B&B) algorithm. The method is able to supply a well balanced and cheap assembly line. The minimal and maximal numbers of stations are computed by solving the classical assembly line balancing problem by assigning to the tasks the fastest resource and the slowest resource, respectively. The GGA is used to assign the tasks to the stations while the B&B algorithm is used to determine the optimal resource for each station.

Sysoev and Dolgui (1999) present an equipment selection problem as a multi-criteria decision making problem. An iterative Pareto optimization method is proposed. The convergence of this method is proved.

Gorlach and Wessel (2007) study the best automation strategy for a car manufacturer. Their research considers the final car assembly lines at three production sites of a carmaker in order to determine the best level of automation for each, in terms of manufacturing costs productivity, quality and flexibility. The results of the analysis indicate that fully automated assembly systems are not necessarily the best option in terms of cost, productivity and quality combined, which is attributed to the high complexity of final car assembly systems; some de-automation is therefore recommended. On the other hand, the analysis shows that low automation can result in poor product quality. Hence a balanced combination of automated and manual assembly operations provides better utilization of equipment, reduces production costs and improves throughput.

Rubinovitz et al. (1993) describe a heuristic algorithm for the design and balancing of a robotic assembly line. The algorithm aims to allocate equal amounts of tasks to workstations (i.e. balance the line) while simultaneously selecting the most efficient robot type among several different robot types available for each workstation, with the objective of minimizing the number of workstations and robots used for a given cycle time. The balancing problem is simplified by the restriction that a single equipment is allowed for each workstation. A branch and bound frontier search method is used as the base of the heuristic algorithm. It builds a search tree by assigning robots and task elements to stations. As a lower bound, the sum of minimal possible times for activities not yet assigned to stations is used. To maintain the huge number of nodes on the search tree, the algorithm may require more storage space than available. It also requires significant computation time. As a result, the Branch-and-Bound based algorithm, even with heuristic rules incorporated to reduce the search space, can be used for solving relatively small problems. This approach has been generalized by Bukchin and Tzur (2000) to design a flexible assembly line when several equipment alternatives are available.

Bukchin and Tzur (2000) consider the robotic assembly line balancing problem with the objective to minimize the total equipment cost given a pre-specified cycle time by selecting the equipments and assigning tasks to workstations. Several equipment alternatives, which have different costs and effects on the task times of the product, are available for each task. A branch and bound algorithm is used to solve small and moderate size problems and a heuristic procedure is developed to deal with large size problems. Their heuristic procedure is a version of the branch and bound algorithm, which skips some nodes by user specified parameters.

Kim and Park (1995) focus on the problem of assigning assembly tasks, parts and tools on a serial robotic assembly line so that the total number of robot cells required is minimized while satisfying the various constraints. Assignment of robots with different performance capabilities is not part of their model. They suggest an integer programming formulation of this problem and a strong cutting plane algorithm to solve it.

Rekiek et al. (2002) present a hybrid assembly line design with two objectives. One objective is to minimize the total cost and the other one is to integrate the design and operation issues. Different from the equipment selection models, the operating modes of the equipments are set as manual, robotic and automated. The model is solved by branch and cut method and the multi criteria decision aid method PROMETHEE II. First, the tasks are assigned to the workstations according to the equal piles strategy, and then all possible resource combinations for each workstation are generated by the branch and cut algorithm. Finally, the best possible combination is selected by the PROMETHEE II for a single product.

Paccarelli et al. (2002) consider the problem of assigning tasks to an ordered sequence of non-identical workstations under the constraints of precedence relations and a given cycle time. The objective is to minimize the cost of the workstations. A dynamic programming algorithm is developed for solving the problem.

In most articles mentioned above, the objective is to assign the robots and tasks to the workstations in a way to minimize the number of workstations or the cost of assembly systems given a cycle time. This problem is classified as the *type I robotic assembly line balancing* (rALB-I) problem. In contrast, a *type II robotic assembly line balancing* (rALB-II) problem determines the optimal robot and task assignments to workstations with the objective of minimizing cycle time (i.e. maximizing the production rate of the line). For example, Gao et al. (2009) propose a hybrid genetic algorithm to solve a rALB-II problem in which when a new product is to be manufactured in the assembly line; the assembly system needs to be reconfigured by using available robots on hand in order to improve the productivity. The objective is to assign tasks to a fixed number of workstations and select one of the available robots in a way to minimize cycle time. Levitin et al. (2009) study a rALB-II problem. They assume that all types of robots are available without limitations and the purchasing cost of the robots is not considered. The objective is to assign tasks to workstations and to select the best-fit robot type for each workstation in such a way that the cycle time is minimized. The problem is solved using two versions of genetic algorithms.

3. FUNDAMENTALS of ASSEMBLY LINE BALANCING

The assembly lines are important flow systems for mass production. Although these types of systems may be different with respect to several characteristics, they all consist of workstations where the parts flow from one workstation to the next. Parts or sub-assemblies are supplied into the workstations from the first station or intermediate stations by a conveyor system until the end of the assembly line. After all operations are completed, the product leaves the line as a final product. The production flow is illustrated in Figure 3.1.

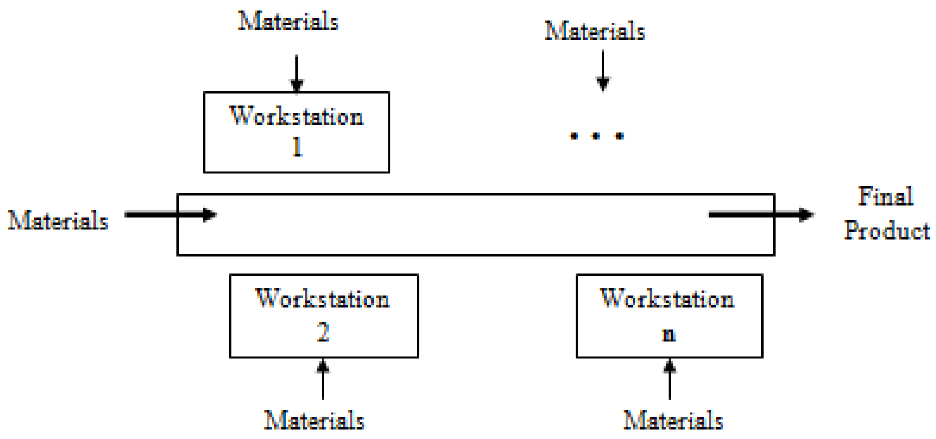


Figure 3.1 Illustration of an assembly line

3.1. Classification of Assembly Lines

There are three kinds of assembly line models according to the product to be assembled: single model, multi model and mixed model lines.

3.1.1. Simple Assembly Line Balancing

Methods for assembly line balancing have been developed in the past. These methods were designed for balancing manual assembly lines. A detailed survey of exact methods for solving the simple assembly line balancing (SALB) problem is provided by Baybars (1986).

There are two main assumptions common to most SALB problem formulations (Baybars, 1986):

a) Task element times are deterministic and independent of the equipment, operator, or station to which the task is assigned.
b) A task can be performed at each station if technological precedence constraints are satisfied, and if the system cycle time is not exceeded by assigning the task to a workstation.

In general, the assembly line balancing problem is to find how tasks are assigned to workstations, so that the predetermined goal is achieved. Minimization of the number of workstations and maximization of the production rate are the most common goals studied in the assembly line balancing literature.

Most of the assembly line balancing models assumes that the equipments of the workstations are fixed and/or the task times associated to different equipments are the same. Moreover, the studies that consider equipment alternatives ignore the purchasing costs.

3.1.2. Multiple Model Lines

In multiple model lines, distinct products or distinct models of the same products are produced by different chunks. Every model on that line forms different chunks. The tasks that are needed to produce these products or models are approximately same. Therefore several kinds of products can be produced on the same line. Multiple model lines can be thought as single model assembly line or mixed model assembly line if chunks are big or small, respectively. For designing multiple model assembly lines, the following steps are required; (Monden, 1983)

i. Cycle time should be determined according to the requested production speed.
ii. Minimum number of essential tasks must be calculated.
iii. Precedence network diagram must be prepared.
iv. Balancing of line
v. Sequencing frequency of different models has to be defined.
vi. Scheduling of products has to be defined

3.1.3. Mixed Model Assembly Line Balancing

Two or more of the same kind of products can be produced concurrently and in mixed order in the mixed model lines. As opposed to the multiple model lines, the customer demands are met by a continuous production system. Automobile production can be a good example of this type of line. Common issues that can occur in mixed model lines include the following:

i. Unequal work flows
ii. Idle station times and redundant stations for basic products
iii. Higher number of stations

For the reasons listed above, mixed model lines usually have complex design problems.

The typical model lines can be seen in Figure 3.2 (Scholl, 1999).

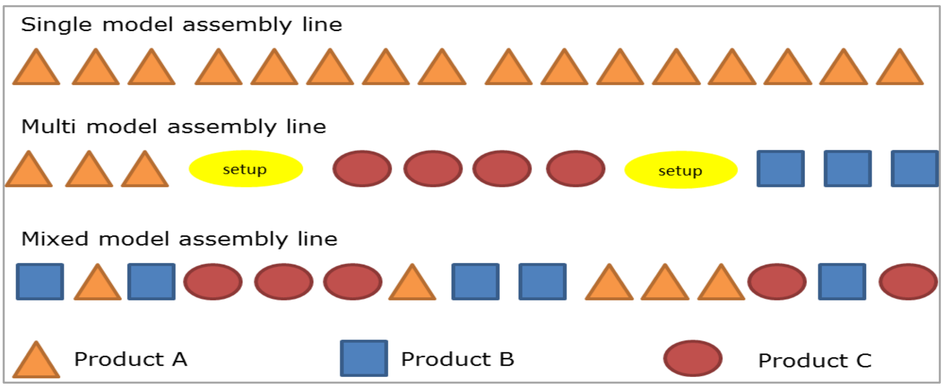


Figure 3.2 Different assembly lines (Scholl, 1999)

3.2. Assembly Line Design

The aim of the many equipment decision problems is the assignment of tasks and equipments to the workstations simultaneously so as to minimize the number of workstations and the system cost including the equipment cost. In the literature, the equipment selection in assembly line balancing problems is frequently referred to as assembly line design problem (ALDP).

The assembly line design problem includes different sub problems such as equipment selection, line balancing, buffers sizing, resource planning and many other related problems. This is done while taking into consideration some technical (throughput rates, available spaces) and financial (fixed and variable costs) constraints (Jeong and Kim, 2000).

Assembly or transfer lines are production systems which are composed of several workstations organized in a serial manner. Each part successively visits each workstation by moving from one workstation to the next by a linear transportation system, for example, a power-and-free system. Serial flow lines have been initially introduced for the production of large amounts of standardized products (mass-production), but are now also used for the low volume-production in a family of products.

The design of assembly lines plays a vital role for the success of manufacturing since it affects the manufacturing cost, productivity and quality.

In order to design an assembly line, the following steps, which are also illustrated in Figure 3.3, are required (Benyoucef et al., 2014):

1. **Product(s) analysis**: the aim of this step is to provide a complete description of the elementary operations to execute in order to obtain the final product(s).
2. **Process planning:** it covers the selection of processes required to obtain the final product(s) and the definition of technological constraints. For instance, a partial order between operations (precedence constraints) is usually defined but various other restrictions have often to be also considered. This step requires an

accurate understanding of the functional specifications of the products as well as technological conditions for the operations.

3. **Line configuration:** this step defines the configuration design which implies the choice of the type of assembly line (e.g., pure serial flow line, hybrid flow shop with parallel stations or U-line), the selection of the equipment needed to perform the operations and the allocation of operations to workstations. It is imperative to consider all the technological constraints. At this step, a security margin often has to be considered in order to take into account failures, quality problems and also possible slight modifications in the product.
4. **Line layout and transport system design:** the material handling system is selected and the layout (placement of machines) is chosen. Products flow is analyzed, usually via simulation, to take into account random events and variability in production.
5. **Detailed design and line implementation:** the commissioning of the machines is performed in this phase. All the machines are installed and tested gradually. In order to test the line & machines speeds, a sample product is produced to check the anomalies

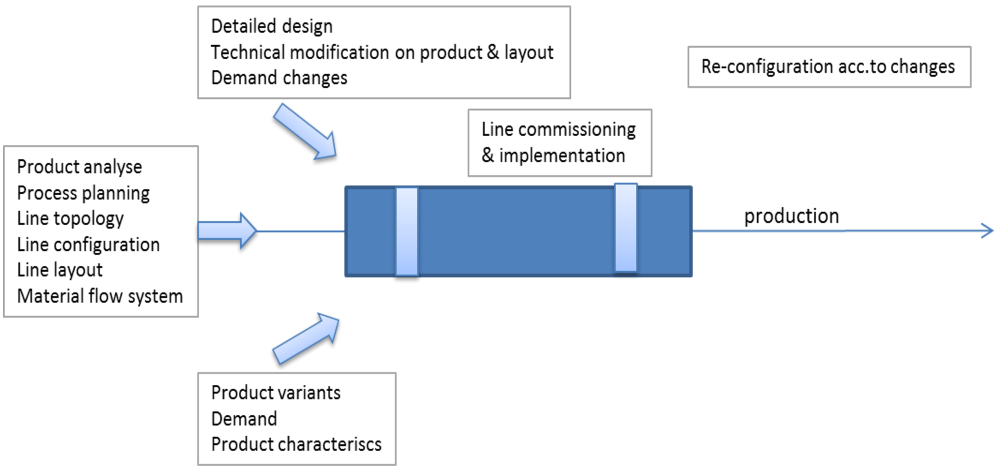


Figure 3.3 Assembly Line Design Important Steps (Benyoucef et al., 2014)

In addition, two other steps can eventually occur after the implementation of the line: (Benyoucef et al., 2014)

- When the line is designed for the production of several products, a scheduling problem has to be considered in order to determine the sequence of the mix of products.
- When the demand is subject to market fluctuations either in volume or characteristics of the product, the line has to undergo a reconfiguration. A reconfiguration has many similarities with the initial design but the existing line induces specific limitations and objectives.

Considering the complexity of the whole problem, these steps are usually considered sequentially. If the goal of the first two steps is to provide information on the process, the third step corresponds to a combinatorial problem with various objectives: minimizing investment costs or future labour costs, maximizing the production rate, minimizing idle times, and smoothing the workload among the workstations.

The assembly line balancing problem is known as finding how a group of tasks are assigned to workstations, so that a pre-determined goal is achieved. Minimization of the number of workstations and maximization of the production rate are the most common goals considered.

The following objectives can be aimed to achieve when constructing an assembly line for the production of a product (Tanyas and Baskak, 2003).

i. Provide an organized or regular material flow
ii. Use the manpower and workstation capacity in an optimal level
iii. Complete the processes in shortest time
iv. Minimize the number of workstations on the assembly line
v. Minimize the idle times
vi. Distribute the idle times among the workstations evenly
vii. Minimize the production cost

The objectives can be conflicting; consequently the main purpose here is to achieve the most reasonable solution by taking these conflicts into consideration. The most important elements considered when balancing assembly lines include the cost of manpower, the size of assembly line (i.e. occupied space) and capital cost.

Some solutions that can be applied when balancing the manpower are listed below (Tanyas and Baskak, 2003).

- **i.** Only one worker can be employed on two or more workstations whose automatic processing time is longer than the others.
- **ii.** Two short processing times can be assigned to one worker, if two jobs are as short as others.
- **iii.** The workload of workers can be increased.
- **iv.** The workers can be ordered according to the speed they are able to perform the task.

3.3. Robotic Assembly Line Balancing

Robotic assembly lines operate under a different set of constraints and assumptions. A different robot, tooling, and assembly equipment may be used at each station, which restricts the tasks to assign to a given station. Task performance times may be dependent on the specific robot and equipment selected for the task. Another difference between manual and robotic assembly lines is in the amount of variation of task times. In manual assembly, the actual task time can deviate considerably from the standard time estimate used for the line balancing. As a result, achieving a "perfect" line balance is of theoretical importance only, and good balances, achieved with the use of heuristic methods would suffice in practice. However, in a robotic assembly line there is almost no variation from the established work pace and task performance times. As a result, any imbalance of the line and idle time at certain workstations will actually reduce system performance (Rubinovitz et al., 1993).

These specific problems of robotic assembly lines, such as variation in task times between manual and robotic station, task time depending on the selected equipment, have been mostly ignored by researchers. Graves and Holmes (1987) presented an optimal algorithm for equipment selection and task assignment for multi-product assembly systems. The system is an assembly line, to which activities and equipment have to be assigned, while satisfying the annual production rate and the assembly precedence constraints. The objective of this work is to minimize total cost, which is composed of fixed equipment and tooling costs, and of variable equipment usage and gripper exchange costs. This objective may be different from an objective of maximum efficiency of the assembly line which is achieved by line balancing. The input to the algorithm consists of equipment costs, task times on different equipment types, and a set of possible assembly sequences. The algorithm finds the minimum cost configuration for a mixed-model assembly line. The main limitation of the algorithm is in using a single assembly sequence for each model. Since most assembled products may be assembled using several alternative sequences, this algorithm finds only a local optimum, and does not take advantage of the assembly task flexibility described by the task precedence diagram. As a result, idle times at each station are not minimized.

4. BASIC CONCEPTS & TERMS IN AUTOMOBILE INDUSTRY

This chapter presents the basic terminology and concepts in automobile industry.

4.1 Definitions of Automotive Terms

The definitions of the key terms related to automobile assembly are provided below:

Workstation

A workstation is a segment of the assembly line where a certain amount of the total assembly work is performed. Each station on an assembly line is set up with all the materials, machines, tools, jigs, clamps, fixtures and operators needed for the operation(s) assigned. A work-piece does not return to a station that it has already visited at an assembly line. A workstation can be robotic (as seen in Figure 4.1) or manual (as seen in Figure 4.2).

Figure 4.1 A robotic workstation with four robots

Figure 4.2 A manual workstation with one manual welding gun

Operator

An operator is a human or robot who performs an operation in a workstation. Human operators perform the tasks manually by using hand tools or task-specific machines. Robot operators complete all the operations in a workstation including the tasks as well as the transfer of parts in-between stations. The transfer may be performed by a human operator as well, but it is not desirable.

Operation (task)

An operation (task) is a portion of the total work content in an assembly process. The time necessary to perform an operation is called operation (task) time. Operations are considered indivisible, i.e. they cannot be split into smaller work elements without creating unnecessary additional work.

In body-in-white (BIW) there are many alternatives to bond two metals together. In our study, we consider several of these bonding forms, which are described below. All weld types are described technically below.

Resistance welding

It is also called as dimensional resistance weld. Welding is a fabrication or sculptural process that joins materials, usually metals or thermoplastics, by causing coalescence. This is often done by melting the work-pieces and adding a filler material to form a pool of molten material (the *weld pool*) that cools to become a strong joint, with pressure sometimes used in conjunction with heat, or by itself, to produce the weld. This is in contrast with soldering and brazing, which involve melting a lower-melting-point material between the work-pieces to form a bond between them, without melting the work-pieces. Many different energy sources can be used for welding, including a gas flame, an electric arc, a laser, an electron beam, friction, and ultrasound.

Resistance welding involves the generation of heat by passing current through the resistance caused by the contact between two or more metal surfaces. Small pools of molten metal are formed at the weld area as high current (1000–100,000A) is passed through the metal. In general, resistance welding methods are efficient and cause little pollution, but their applications are somewhat limited and the equipment cost can be high.

Spot Welding is a popular resistance welding method used to join overlapping metal sheets of up to 3 mm thick. Two electrodes are simultaneously used to clamp the metal sheets together and to pass current through the sheets. The advantages of the method include efficient energy use, limited work-piece deformation, high production rates, easy automation, and no required filler materials. Weld strength is significantly lower than with other welding methods, making the process suitable for only certain applications. It is used extensively in the automotive industry-ordinary cars can have several thousand spot welds made by industrial robots in general. Furthermore, spot welding is a welding process with no material addition, through electrical resistance to current. Electrodes are responsible for generating current to weld the sheet metal parts. Through resistance to current, welded material is made molten and then held together long enough to bond (approx. 0.75-1.5 seconds). Composition of spot weld is shown in Figure 4.3.

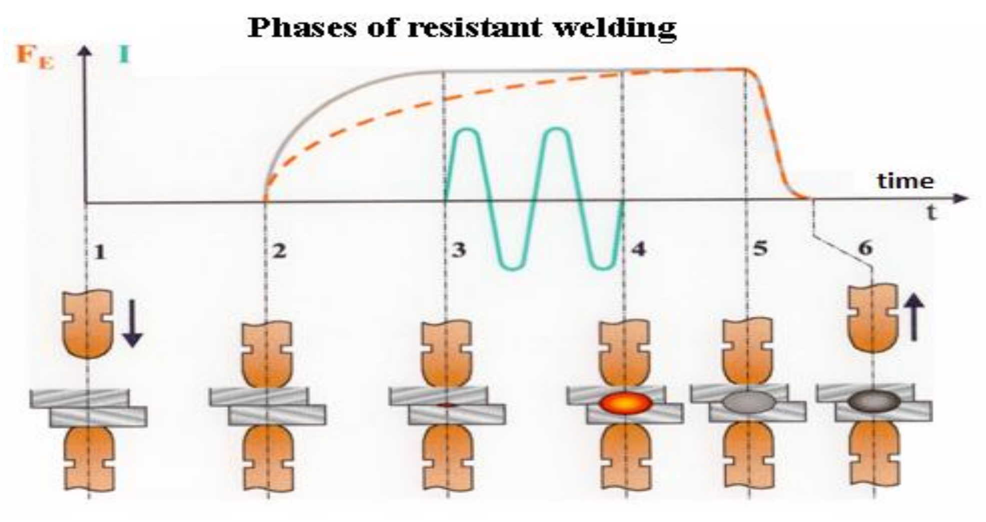


Figure 4.3 Spot weld composition phases

Stud Weld

It is like arc welding process, similar to spot welding. Drawn arc, Short arc or Gas arc welding processes can be used, where a stud is fixed onto a sheet metal as shown in Figure 4.4. The electrical arc is generated between the stud and the base metal, this region is molten and then both parts joined, similarly to the spot weld. It is commonly used for instrument panel and power steering fixtures, heat shields, lighting systems, exhaust systems, wiring harness routing and trim (Wayman, 2009).

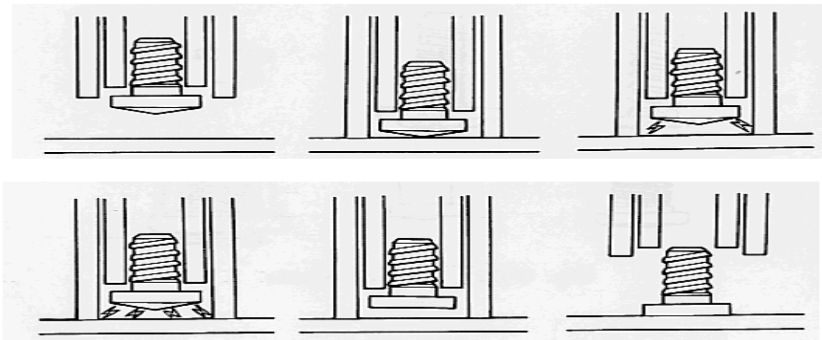


Figure 4.4 Stud Weld Connection

Projection weld (Weld Nut)

It is a variation of spot welding, using projections as current concentrators. It also uses electrodes to induce current and melt the parts together as shown in Figure 4.5. Projections are designed in one part and these act as current concentrators for the welding process. When the two parts are mated together, these projections are the high points that first make contact. As electricity goes through, the projections simultaneously carry the current and are welded (Wayman, 2009).

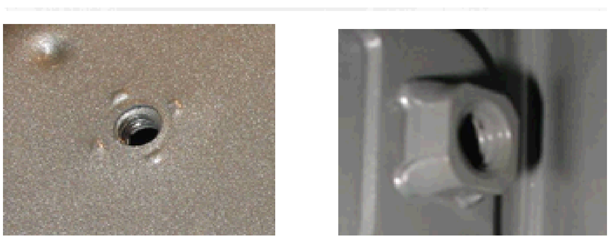


Figure 4.5 Weld Nut Connection

Riveting Connection

Joining of sheet metal parts is performed with metal stamping and forming, using a rivet as a connecting element as shown in Figure 4.6. If the parts do not have previous boring, metal stamping of the bores is also needed. Metal joining is done mechanically, with no thermal influence, using the rivet as a connecting element. Shear strength increases when using a washer in addition to rivet closure (Wayman, 2009).

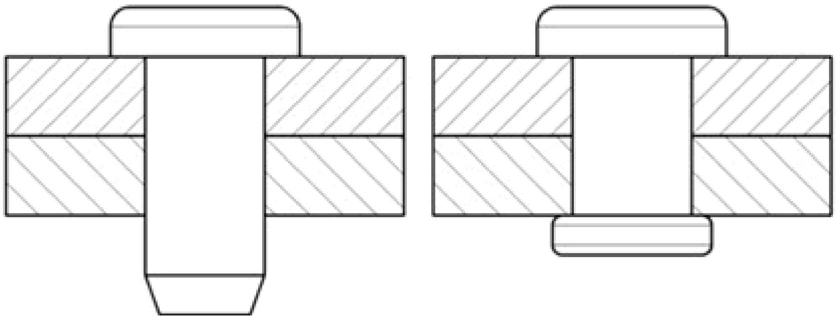


Figure 4.6 Riveting Connection

Clinch Connection

Two sheet metal objects are joined through metal forming (punch and die), as shown in Figure 4.7. There are no burrs or sharp edges for this joining type that have corrosion. This type of joining is an option to spot welds, and it has no thermal influence. Punched region can also be filled with a rivet (Wayman, 2009).

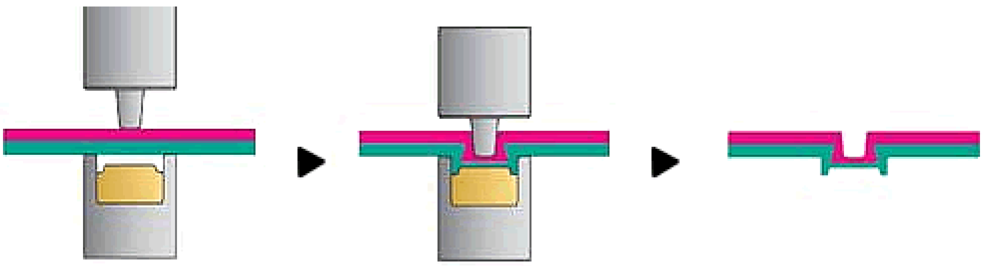


Figure 4.7 Clinch Connection

Hemming Connection

Joining of sheet metal parts are performed with metal forming on sheet metal edges. Two sheet metal parts are bonded together. Those are joined through metal forming, either through roller or punch and die hemming as shown in Figure 4.8. It obtains tight flanged connections, limited to sheet metal yield strength. It is commonly used for doors, hoods, side inner and outer panel joining (Wayman, 2009).

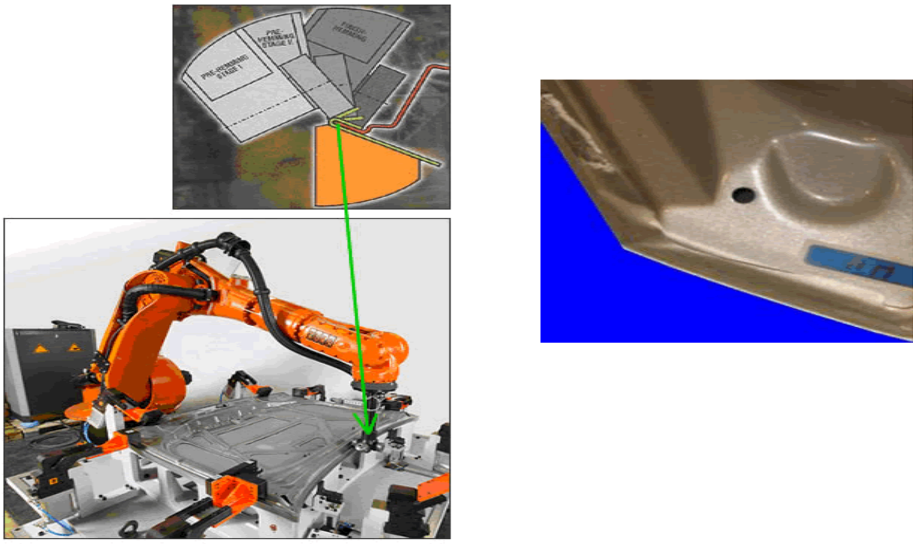


Figure 4.8 Hemming Connection

Laser Welding

This technique provides the possibility of narrow and deep parts joining, due to highly concentrated heat source, high power density, which allows small heat affected zones, high heating/cooling rates, deep welding. No filler/flux material is needed. It possesses faster welding rates and low material distortion (Wayman, 2009).

Brazing

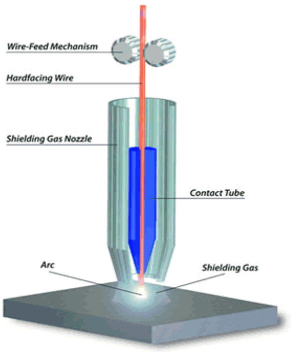
Joining process is performed with no base metal melting, using molten filler between base parts. It has less temperature than common welding process (only filler + flux are heated). The used filler penetration into base metal is through capillary action. The process is easily automated and with better surface finishing (Wayman, 2009).

Laser Brazing

Laser brazing method combines the advantages of common brazing and laser heating. It has better temperature control of filler melting temperature. The usage of laser (concentrated heat source) onto filler material does not jeopardize parent material. Laser brazing creates smaller heat affected zone once welded. Usage of filler produces a continuous weld seam. It is faster than common brazing process (Wayman, 2009).

CO_2 / MIG / MAG weld

It is traditional metal arc welding with either inert or active shielding gas. CO_2 welding is also called arc welding process. A DC arc burning reaction takes place between a thin metal wire electrode and the work-piece, enveloped in a protective gas shield (either inert or active gas shield) as shown in Figure 4.9. A consumable wire electrode is used for this type of weld, which is fed from a spool and through a welding torch. This causes spatter, which needs to be sanded or ground (Wayman, 2009).



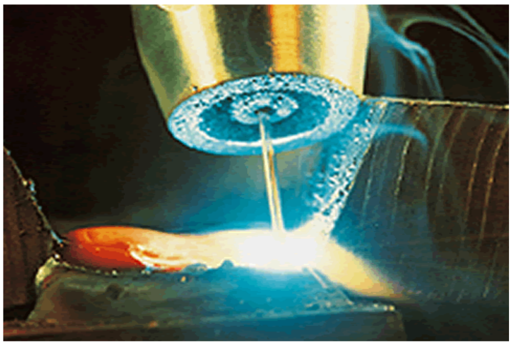


Figure 4.9 CO2 Connection

TIG weld

It is an arc weld with inert shielding gas and has no consumable tungsten electrode. DC arc burning reaction does not take place between a non-consumable tungsten electrode and the work-piece, enveloped in a protective inert gas shield (usually argon). It may or may not have a filler material. There is a wide range of material that can be welded through TIG process. It does not cause spatter, and is cosmetically better than MIG/MAG welding but more expensive than MIG/MAG welding (Wayman, 2009).

Structural Adhesive

It is an option to bind together not only metal but different materials such as plastic, glass, carbon fiber. Most common are epoxies compounds, made of two items: organic bonding resin and a catalyst. There are basically two types of epoxies: glassy matrix epoxy (acrylics) and polyurethane epoxy. Adhesives are most used for: bonding parts of different nature together (plastic/glass with metal), and adding mechanical strength to welded parts (Wayman, 2009).

Screws / Nuts

Joining process is performed through mechanical interface, using torque application between parts as shown in Figure 4.10. A screw is a shaft with a helical groove or thread formed on its surface and provision at one end to turn the screw. It can also be called a bolt. A nut is a type of fastener with a threaded hole. Nuts are almost always used opposite a mating bolt/screw to fasten a stack of parts together. The two partners are kept together by a combination of their threads' friction, a slight stretch of the bolt, and compression of the parts (Wayman, 2009).

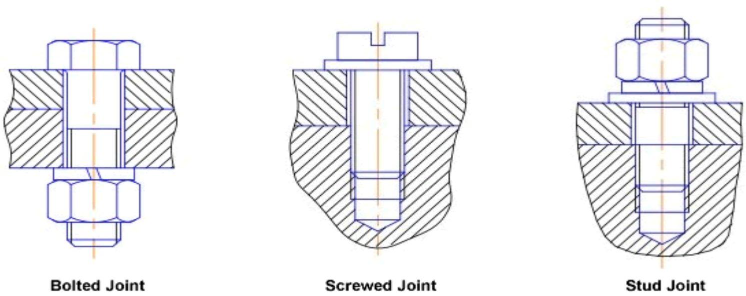


Figure 4.10 Screws/Nuts Connection

In our study, spot welds are generally considered to give the material its geometry. A few spot welds compose a task, which is considered to be a non-divisible task.

Re-Spot Weld is similar to spot welding; there is no difference at all technically. Sufficient spot welds are performed to the material in order to give the geometry, but these welds may not be enough to satisfy the rigidity. The remaining welds can be performed entirely in a single workstation or they can be assigned to different workstations if preferred so. These remaining welds to satisfy the rigidity of the material are simply called as respot weld, which may be assigned to a workstation as a whole or partly, hence a respot task is considered to be a divisible task.

Today, the science continues to advance. Robot welding is common in industrial settings, and researchers continue to develop new welding methods and gain greater understanding of weld quality and properties.

4.2. Precedence Network Diagram

Due to technological restrictions, the ordering in which operations must be performed may be pre-specified. This ordering of tasks can be illustrated by means of a precedence diagram which contains nodes for all operations and arcs (i, j) if an operation i must precede an operation j. An example of a precedence diagram is given in Figure 4.11. The number of spot welds is denoted above the node. In this example, task 3Y01 must be performed before tasks 3T03 and 3T04; task 3N01 prior to task 3T01 and 3T02, etc.

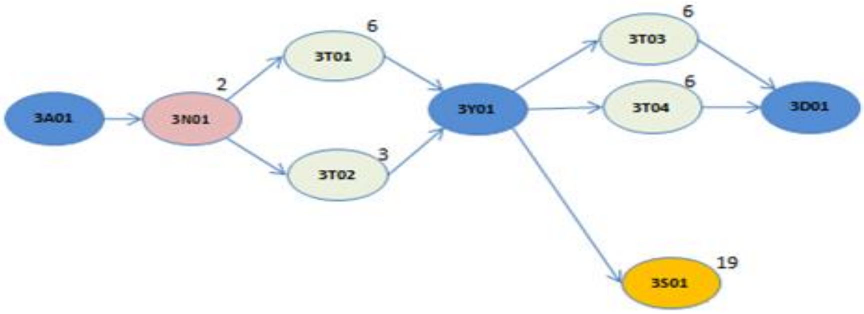


Figure 4.11 Illustration of a Precedence Network Diagram

4.3. Time inputs

The following section describes the different time parameters that exist in the production system.

Operation time

Operation time is the time to complete a task in a station. Operation times are dependent on the equipment which a task is assigned to. Measuring operation time is either made manually by stop-watch, or digitally by image processing techniques. In this study, the operation time for a task is measured multiple times and the average value of these measurements is considered as the task time.

Workstation Time

The workstation time is the sum of the durations of the fixed activities (non-value added activities) and the equipment-dependent durations of the tasks that are assigned to a workstation. That is, it is the time difference between the starting time of the first task assigned to a workstation and the completion time of the last task. The workstation time should not be greater than the takt time. An example for workstation time is shown in Figure 4.12.

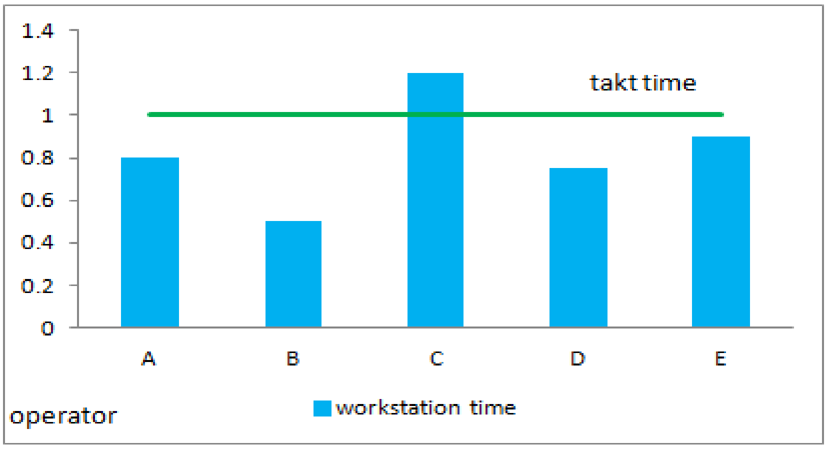


Figure 4.12 Workstation time vs. Takt time

Cycle Time

Cycle time is defined to be the time from the time a task or series of tasks is initiated to the time a task is completed. For example, cycle time of a machine can be simply measured by timing how long it takes from pressing the button to start the cycle for the first work-piece to the pressing the next button for the next work-piece.

Since tasks are divisible and indivisible in our case, the cycle time can be no smaller than the largest operation time of a task within our case. In unpaced flow-line production systems (including mixed model lines), the cycle time serves as maximal possible average station time.

A positive difference between the cycle time and the workstation time is called idle time, because the operator is idle after performing the workload in-station or he works continuously at a slower pace. In this case, the performance loss takes place.

Takt time

Takt time can simply be defined as the production rate required to satisfy the demand for the product. In other words, it is the time that must elapse between two consequent product completions. Hence, takt time is a function of product demand and available production time (Ortiz, 2006), and it is calculated as the ratio of the production time available to the demand volume for the product.

$$\boldsymbol{C = T/D} \tag{4.1}$$

***C*:** Takt time
***T*:** production time available (excluding breaks, meeting times)
***D*:** the demand volume for the product

Cycle time of an assembly line ideally should be equal to the takt time in order to synchronize the production rate with demand rate of the product.

Takt time can be divided into three sub-durations; **productive work time, unproductive work time, idle time**. Various time components are shown in Figure 4.13.

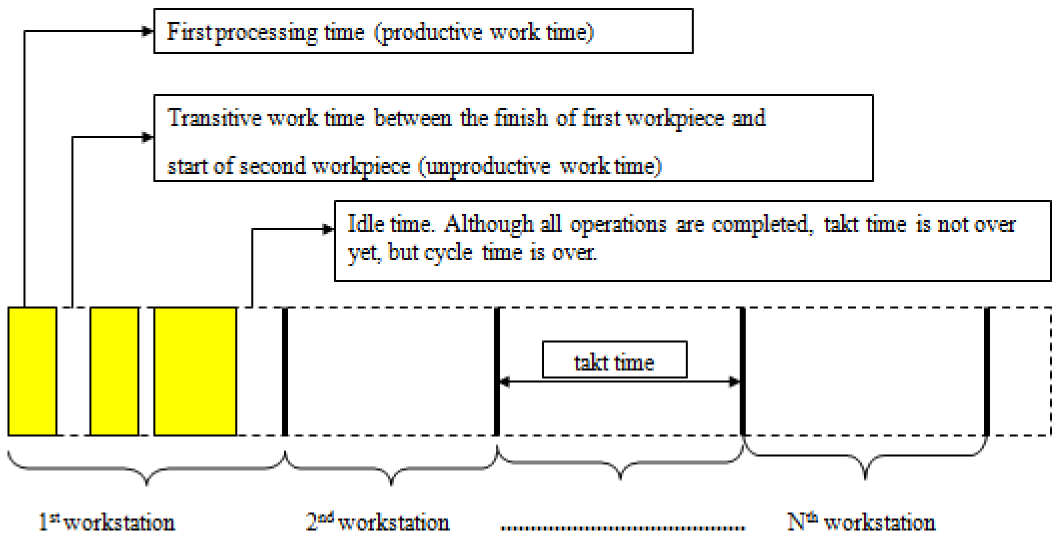


Figure 4.13 View of time parameters splitted in a workstation

4.4. Automation Level Calculation

Harbour Report™ is a guide to the automotive manufacturing worldwide, and is a leading competitive analysis tool utilized by the original equipment manufacturers (OEMs) and suppliers in order to benchmark the performance, to develop strategies, and improve operations (Wayman, 2009).

For the weld assessment, the auto experts collect data (by type of weld / fastener / adhesive etc.) on the number of total welds in the vehicle, and the number of welds performed at the plant. All welds are converted to “spot weld equivalents” based on the amount of work required to perform that type of weld. Equivalent spot weld coefficients for several operations are given in the Table 4.1. The coefficients here are mostly a combination of time and rigidity.

- For each model of the car produced in the plant, automakers provide the number of welds for spot welds, stud welds, nut and screw welds and length of joining for sealing and arc welding. Number of weld point is not enough to convert to the equivalent spot weld; therefore it is important that which technology is used for joining. In addition, it is also important how many welds are performed in-house for comparison with other models in different plants.
- All welds are then converted to an equivalent spot weld in order to calculate the % of equivalent spot welds performed in-house.

Table 4.1 Equivalent spot weld coefficients

Operations	Equivalent Spot-Weld
Spot Welds	1
Stud Welds	1.5
Weld Nuts	1.5
Rivets	3
Clinch connection	1.5
Hemming connection (mt)	14
Laser (mt)	78
Laser Brazing (mt)	74
Brazing (mt)	140
CO2/MG/MAG - Weld Steel (mt)	68
Structural Adhesive (mt)	14
Screws	3
Nuts	2
MIG/TIG - Weld Aluminum (mt)	140

According to the Harbour Report methodology, the automation level is calculated using formulations *a* to *c*, which are explained below (Wayman, 2009).

Formulation *a* indicates how to calculate the total equivalent spot welds performed in-house to produce the vehicle. Formulation *b* indicates how to calculate the total automatic equivalent spot welds performed in-house. Formulation *c* indicates the calculation of the percentage of automation level.

a. Total Welds-Equivalents Performed In-House in Vehicle = Number of Spot Welds in-House in Vehicle + (Number of Stud Welds Performed in-House in Vehicle x Equivalent Spot Weld Factor: 1 Stud Weld = 1.5 Spot Welds) + (Number of Weld Nuts Performed in-House in Vehicle x Equivalent Spot Weld Factor: 1 Weld Nut = 1.5 Spot Welds) + etc. for each applicable technology. (4.2)

b. Total Welds Performed In-House Automatically in Vehicle = Number of spot Welds-Equivalents Performed In-House Automatically + Number of Stud Welds Performed in-House Automatically in Vehicle x Equivalent Spot Weld Factor: 1 Stud Weld = 1.5 Spot Welds) + etc. for each applicable technology. (4.3)

c. Total Percent of Automation = b / a x 100 (4.4)

In our study, all phases are conducted in the make process. That means all inputs are collected in the processes performed in-house, not an outsourced part or process. When the number of equivalent spot welds performed automatically is divided by the number of all equivalent spot welds, automation level is calculated automatically for our project.

4.5. Automobile Design Phases

In this section, the design phase of an automobile is described and industrialization of a model is explained.

4.5.1. Design Phase

Introducing a new model of automobile generally takes three to five years from the inception to the actual production. Ideas for new models are developed in order to respond to unmet public needs and preferences. Trying to predict what the public wants in five years is no small work, yet automobile companies have successfully designed automobiles that fit public tastes. With the help of computer-aided design, the designers develop basic concept drawings that help them visualize the proposed vehicle's appearance. Based on this simulation, they then construct clay models that can be studied by styling experts who are familiar with what the public is likely to accept. Aerodynamic engineers also review the models, studying air-flow parameters and doing feasibility studies through crash tests. Only after all models have been reviewed and accepted, the tool designers are permitted to begin building the tools that will manufacture the components of the new model. The car design project is graphically illustrated in Figure 4.14. This approach is special to the carmaker in Turkey where we made our study together

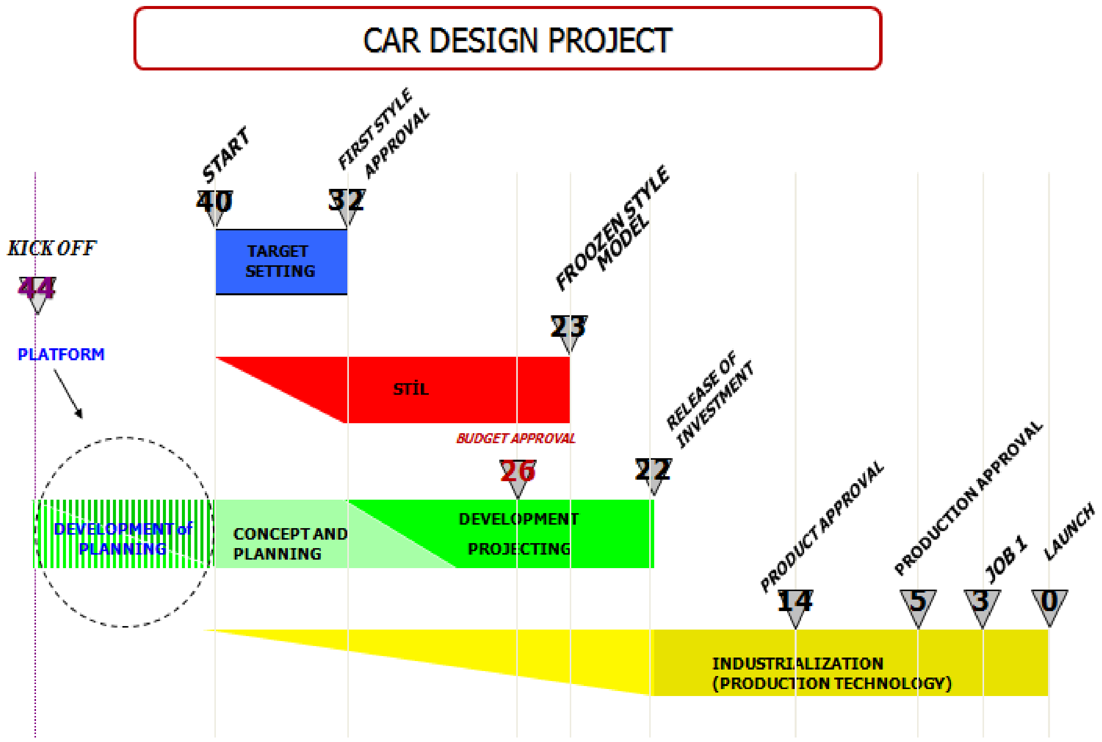


Figure 4.14 Car design phases

4.5.2. Industrialization Phases

This section introduces the vehicle assembly line design phases. Macro activity chart of a technology development unit is shown in Figure 4.15. Design phases of assembly line technologies are explained below.

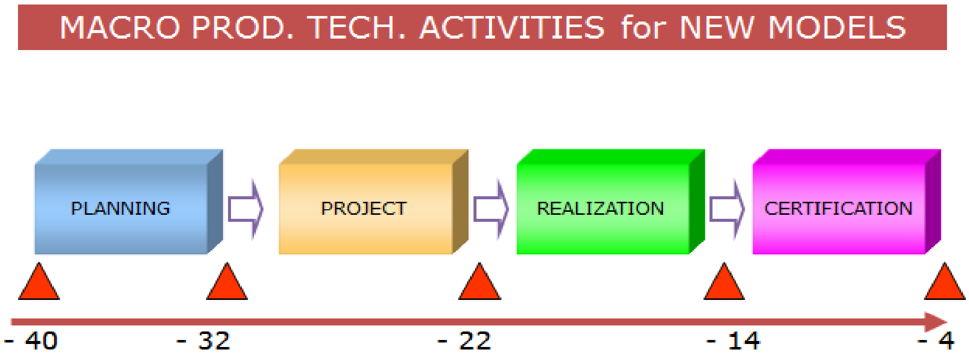


Figure 4.15 Macro activities for new model development (in months)

Planning

Before a new model launch to the market, industrialization of the product is planned.

The following activities are done in the planning phase:

- Defining the production technology system logic and flow: Rough planning on the number of stations, buffer capacities, transport and transfer system, retooling if any, are performed.
- Analyzing the production technology with the prototype vehicles. Product and method changes are made.
- Making a decision on make & buy parts.
- Determining the budget of the project based on the operations performed in-house and labor time available for the production of the vehicle.
- Evaluating the innovative process technology technically and financially.
- Defining the competitive targets of the vehicle after the serial production starts.
- Number of spot welds (the less spot weld, the more competitive), number of stamping operations, efficiency of sheet metal usage, flexibility of the production system, easiness of maintenance, line productivity activities are worked on this step

- Defining the quality targets of the production processes. Cp-Cpk values of critical operations, overall equipment efficiency (OEE) figures, and single line efficiencies are some important KPIs.

Project

After planning phase, Project Phase comes. All the pre-studies to industrialize the product are projected deeply. The project phase includes the following activities:

- Feasibility of processes is analyzed in computer-based platform. Internal and external trim models are assessed through the automobile know-how, standards and norms.
- Modifications and improvements of processes are transferred to the design team by checking virtually the technical drawings of the vehicle model according to the targets given in the planning step.
- Macro-operations flow plan, which is simply the assembly of parts to final product, is prepared.
- Pre-method & complete method studies are performed and documented.
- Tolerance analyses are performed according to the requested dimensional targets.
- Process FMEA is performed.
- Technical support is given to the design team when the project FMEA is done.
- Control plan is prepared with the design team and quality control unit.
- Ergonomic analyses are performed. Flow simulation and process simulations are performed in this step to verify the project and process methods.
- Testing the methods of processes during the prototype vehicles and following the modification list up closely

Realization

Commissioning of the project is realized after planning and projecting the product for a period. The realization phase includes the following activities:

- Preparation of technical specifications of the machines, facilities, tools and equipments,
- Definition of the machine parameters and line parameters,
- Projecting assembly line layouts,
- Projecting the material flow system and infrastructure,
- Projecting the workstation details, e.g. layouts, tools,
- Technical Audit on subcontractors during Projecting, Manufacturing, Assembly, Commissioning and Test production phases,
- Preparing the process planning cards.

Certification

At the end, the project is certified. During this phase, the following activities are included:

- Certification of the processes via standard check-lists. Finding solutions on the potential problems.
- Certification of the workstations via standard check-lists. Performing any missing item or nonconformities on the workstation.
- Following up the problem list managed by the project and quality team together. Finding the solution to any unsolved problem.
- Performing the test of assembly of direct parts on the vehicles to verify the process.
- Process improvement activities are planned to realize the quality targets.
- Providing the technical support to achieve the production targets during the ramp-up period.

4.6. Vehicle Manufacturing Phases in an Automobile Plant

The production of a car usually follows a standard process, which is explained below and illustrated in Figure 4.16.

Stamping: The steel sheet is cut according to the size of the part. It is bent and cut in a stamping machine.
Welding: The stamped parts are heated and melted to be joined together.
Painting: The cars are painted with 3 coats.
Making the Engine: The parts are produced by casting and forging. These parts are then used to assemble the engine and suspension.
Assembly: The parts are attached according to the customer's orders.
Inspections: The inspections are made on the brakes, combustion system, acceleration system, fuel system, toe alignments and other assembled parts.

Once all of the phases above are completed, the cars are shipped to destinations around the world using an appropriate transportation mode.

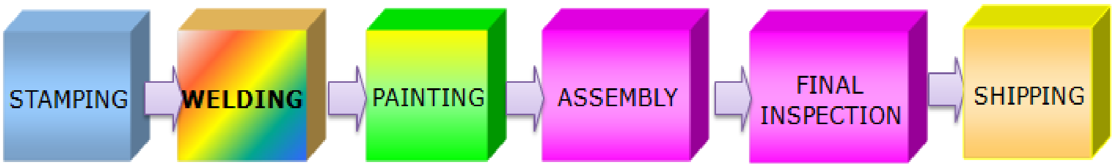


Figure 4.16 Car manufacturing standard processes

4.7. Body Shop Design

Welding or Body shop floor, where the chassis of a vehicle is composed, is also known as Body in White (BIW) in the automotive literature.

The design and production phases of a body shop floor are introduced in this step.

4.7.1. Designing Body Shops

A well-designed shop produces cars that the marketing department requests. The costs include the money to build the shop and the money to run it. Designers of manufacturing systems must determine (1) the parameters that affect shop efficiency such as buffer sizes and locations, assembly lines' efficiency, and cycle time; and (2) a control policy that allows the shop to deliver the right products at the right time without degrading its efficiency (Patchong et al., 2003).

In the conceptual phase of the body shop design (Moon et al., 2006); the technical details of the product are uncertain used for the design of the car. The drawings of the new car, the production rate target, and the available space are given to the engineers. In most automotive industries, the production rate target is usually represented as unit car per hour (CPH). CPH means the number of cars produced per hour. Assume that the target is set as 40 CPH and that the available working time of one shift is 420 minutes (7,5h with a 30 min break); then, the Takt time is calculated as 60/40 = 1,5 min/car or 90 seconds per car and 420/1,5 = 280 car per shift.

In this step, the engineers should know the downtime rate of the sub-line in order to determine the numbers of stations and the equipment. The downtime rate is usually determined based on a similar production line. If the estimated rate is 10%, the takt time is set as 90 x 0.9 = 81s. This value means that all operations in the line should be finished within 81 s. (including the transportation time to the next station).

Next, the number of stations in the sub-line is determined, and the welding tasks are distributed to each station.

Figure 4.17 shows an example of the process time design of the rear under-body line. The time of each station is the sum of transfer time and processing time. After determining the cycle time and efficiency ratio, the type of robot and the material handling system for the sub-line is considered.

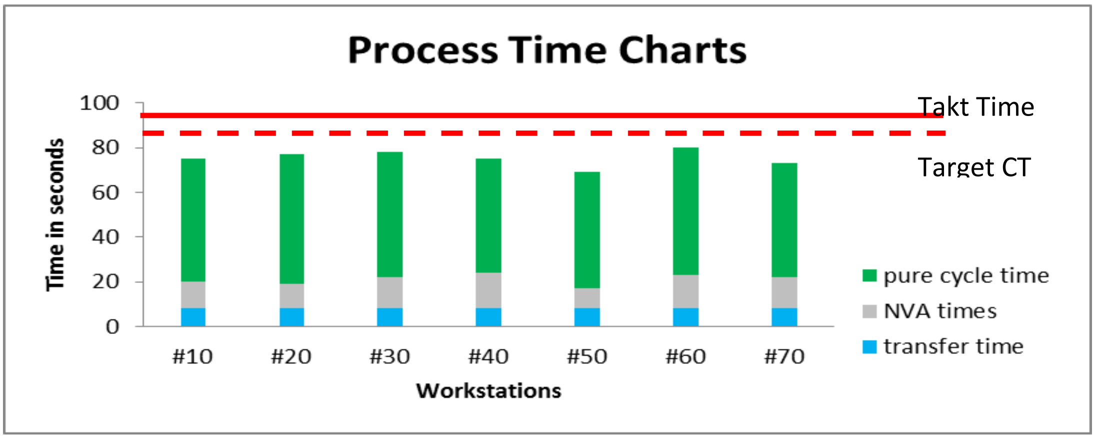


Figure 4.17 An example of process time chart

After preparing the initial designs of all sub-lines, the system simulation of the body shop starts. In this stage, most robots and the type of material handling equipment connecting two sub-lines are already determined. The missions of material handling equipment are transportation and storage space. Power-and-free conveyor or electro motor system (EMS) is usually selected for the system. The main interests in the system simulation are whether the body shop achieves its production quantity target (CPH) or not, and the search for the best layout if current layout does not achieve the target.

4.7.2. Manufacturing in Body Shops

When an automobile manufacturer develops a new car model, this requires new production lines to be constructed or the existing lines to be reconfigured. Especially, the body shop needs to be entirely rebuilt when a new car model is developed unless it is a face-lift model that necessitates only a few minor changes in an existing model. Even for a face-lift, the changes in the body shop are relatively more difficult to make than in the other shops.

The body shop is a typical example of the flow shop or the transfer line. Generally, a body shop consists of several sub-lines such as the underbody joining line where the rear, central and front floors of the car are joined, the framing line where the underbody, the right and left body sides and the roof are joined, the re-spotting line, the body-in-white (BIW) assembly line that joins the main frame, the doors and bumper traverse, and finally BIW finishing and rework line, as illustrated in Figure 4.18.

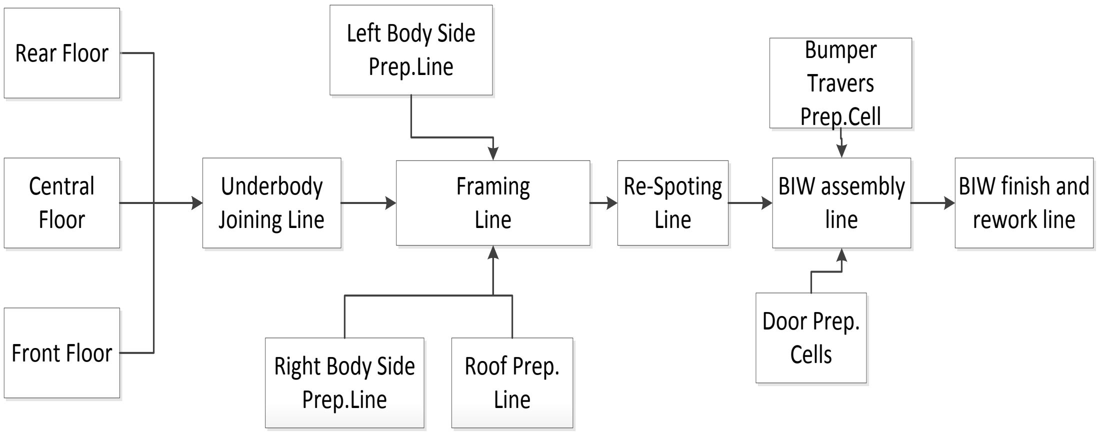


Figure 4.18 General composition of a body shop

Generally, the underbody is the largest body component to which a multitude of components and braces will subsequently be either mostly welded or bolted. As it moves down the assembly line, held in place by clamping fixtures by robots in general, the bottom part of the vehicle is built. First, the front and rear floors are produced in a different area and brought by a transportation system to the beginning of the underbody line, respectively. Then, the central floor is produced in a different place and transported to the underbody line. All three sub-assemblies are joined together, beside several parts are being assembled additionally. [1]

The body is produced on a separate assembly line from the chassis called framing. Robots perform most of the welding tasks on the various components, but operators are necessary to place the parts together on the welding fixture or to a conveyor feeding the robotic cell. Components are held strictly in a jig while welding operations are performed. The left and right body side panels, inner and outer pillars and roof are assembled in the same fashion. The body-shell of the automobile is composed in framing line. Underbody, left and right body side are held by jigs or technological machine arms in a stiff manner. Here the process continues to shape a car by the use of robots. If we selected the framing line to model instead of front rail line for our case study, we would assign this task to an automatic station because high-tech robots can

[1] How Products are made. (2013). How Products are made. URL: http://www.madehow.com/Volume-1/index.html . [Accessed December, 2013].

easily weld the joining points to each other and perform a high number of weld operations in a time frame and with a degree of accuracy no human workers could ever approach. Another reason for assigning to robotic station is that the components get heavier when assembled together. Robots can get roughly 80-100 kg roof panels and place them precisely in the proper weld position with very small tolerance variations.

As the body proceeds from the framing line, subsequent body components including fully assembled doors, engine hood panel, right and left fenders and bumper reinforcements are installed on the finishing assembly line. A full production of the body is completed at this moment on this line. Although special equipments or robots help operators place these components onto the body shell, the operators guide the proper fit for most of screwable parts using pneumatically operated tools.[2]

Once the body-shell is complete, it is attached to an overhead conveyor for the painting process. The multi-step painting process includes inspection, cleaning, degreasing, coating while dipping electro-statically applied, drying in ovens of 200^{o}C, topcoat spraying, and finally baking.

The sub-lines are connected by a transportation system such as electric mono rail system, power-and-free conveyor system or skid system. In each sub-line, a main assembly (e.g. underbody, main frame, body-in-white) is produced by adding to each other several parts produced in-house or purchased from suppliers (known as *make* or *buy* parts) using some joining methods such as spot welding, stud welding, nut welding, arc welding, riveting, clinching, hemming, laser welding, brazing or using adhesives.

In a body shop, a joining task may be performed manually by an operator, automatically by a robot or through an operator-robot mixture module in which an operator feeds the robot with a part or material and the robot performs the operation. Each joining method has different processing times depending on whether it is a manual method or a semi-automatic or automatic process.

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[2] How Products are made. (2013). How Products are made. URL: http://www.madehow.com/Volume-1/index.html . [Accessed December, 2013].

4.8. Automation in BIW

Automotive manufacturing is a complicated process that requires **automation** to some extent. The level of automation is a strategic decision that should be made during the initial phase of the car manufacturing project that starts with the conceptual design. Automation level affects significantly the capital investment; therefore careful analyses are required to determine the best level of automation.

The level of automation is affected by many parameters. Each level of automation is associated with these aspects; costs, quality, flexibility and efficiency as well as productivity.

Labor cost is the decisive factor on the automation due to the aspects of quality, cost and flexibility. Labor behaviors and faults can change with respect to the culture, and its cost changes according to the welfare of the country that an investment is planned. A list of labor cost change in many of the developed countries is in years 1990-5 and 2001 in Table 4.2. One can conclude that the increase in labor cost led to the companies to convey their investment in low-labor cost countries, but the automation does not necessarily remain in the same level. The optimum level must be determined considering many parameters.

Table 4.2 Hourly labor cost in automotive industry

Countries	Labor cost in 2013 (€/hr)
Turkey	8.50
Germany	45.00
Italy	26.00
China	2.50
Mexico	5.00

5. PROBLEM STATEMENT

In this study, we consider the problem of automation level optimization for an automobile manufacturing plant in Turkey. For privacy reasons, the name of the plant is kept anonymous. In this plant, until a decade ago, the decisions regarding the automation level for the car assembly lines were made based mainly on the team leaders' or engineers' past experiences, i.e. no careful technical analyses were made. Their approach was to determine the workstation types (i.e. manual, robotic or semi-automatic) to be used in an assembly line in an ad-hoc manner, and construct the line without a pre-evaluation phase. This approach was not good in finding the line configuration having the best automation level. Even if better levels of automation are discovered after the production starts, it would be very costly to change the workstation types because of their high capital investment cost. Later, in the last decade, with the high advances in technology that created computers with better computational power and lower cost, a simulation method is adopted by the firm to evaluate several alternative line configurations designed by the engineers before their actual implementation. The construction of the line starts once a line configuration that satisfies the desired productivity at a reasonable cost is found after the simulation analysis. Clearly, this is a more cost-efficient and effective approach than the former approach. However, this approach is not necessarily providing the optimal automation level that satisfies the desired productivity level at the minimum cost.

We propose a mathematical programming model to determine the optimum automation level for an automobile assembly line. The problem we consider is described in details in section 5.1, and the proposed mathematical model is presented in section 5.2.

5.1. Problem Description

A new commercial vehicle model is to be manufactured in this plant, which requires the body shop to be redesigned completely. The aim is to determine the right level of automation. In this study, we consider the front floor of the main body for this vehicle as an example for developing the methodology. The reason for choosing this part of the car is that the assembly of front floor includes the main operations that the other parts of the car as well require such as spot, stud or arc welding. The front floor line of the car consists of several sub-assembly lines, as illustrated in Figure 5.1. The sub-assemblies are given letter names (i.e. A, B, C) for confidentiality in Figure 5.1. Among the sub-assemblies of front floor, we choose the *right front rail preparation line* for the formulation of the mathematical model proposed for automation level optimization, but the model can be easily modified to fit the other sub-assembly lines.

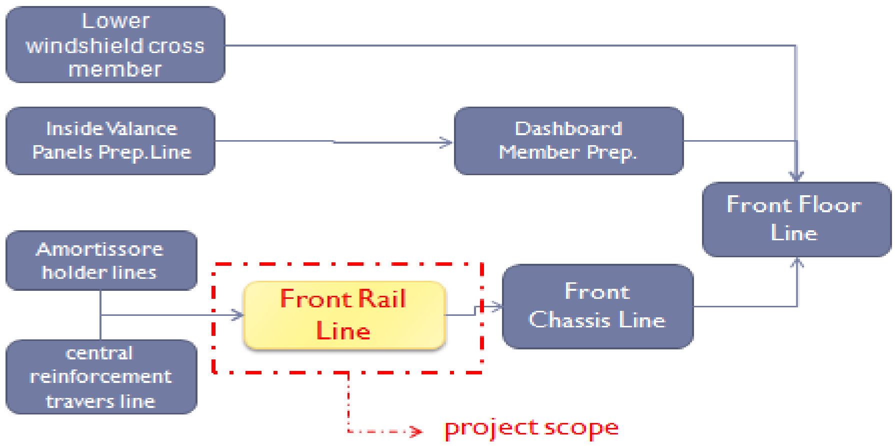

Figure 5.1 Composition of a front floor

The technical drawings of the new model, estimated annual production volume, and the available space for the line are known to some extent during the investment phase. There are different versions of the car whose main assemblies may be fairly different. This means that when a complex model is produced, more resources are required. However when a simple (or base) model is produced, less resources are required. Since the mix-production is planned in this plant, the manufacturing system is designed considering the most complex sub-assemblies among the different versions of the car model.

The objective is to design an assembly line with the optimum automation level which minimizes the total system cost. The system cost consists of many cost components such as the fixed purchasing cost that includes the purchasing and commissioning costs of the equipment modules, the variable operating cost that includes the direct and indirect labor cost, the indirect material cost, idle time cost, and the fixed operating cost that includes area cost, stand-still energy cost and spare part cost.

We propose a mixed integer programming model for this problem, which is presented in chapter 5.2. The proposed model will be solved using the integer programming solver, Cplex. The optimal solution of the model will include the following decisions regarding the assembly line:

- Types of workstations and the equipment / the number of operators or robots
- The task assignments to workstations

The optimal automation level is calculated using the optimal solution (i.e. workstations types and task assignment to workstations) of the proposed model. The type of workstation determines whether a task assigned to it is automatically performed or not. Automation level is defined in terms of the amount of spot welding. If an operation other than spot welding is performed in the line, these operations are converted into an equivalent amount of spot welding in order to evaluate all tasks on a common basis (Wayman, 2009). The total equivalent spot-welds of all the automatically performed tasks divided by the total equivalent spot-welds of all tasks performed manually or automatically gives the automation level, as shown below.

$$Automation\ level = \frac{\text{total spot welds-equivalents of the automatically performed tasks}}{\text{total spot welds-equivalents of all tasks}} \qquad (5.1)$$

5.2. Mathematical Programming Formulation

In this section, the problem of automation level optimization for an automobile assembly line is formulated as a mixed integer programming model. The following assumptions are made in the model:

i. The tasks (except the ones that consist of only respot welding operations) are not divisible, i.e. a task has to be done completely in a single workstation. A respot welding task can be partly assigned to multiple workstations and is divisible.
ii. The technological precedence relations among the tasks are known.
iii. Potential workstation types that can be used for the assembly process and their corresponding costs, capabilities and task processing times are known. A workstation can be manual, automated (i.e. consisting of only robot processors) or a track system (i.e. consisting of both conveyor and robot). All equipment required by the workstations will be purchased. Retooling is not considered.
iv. Task times are deterministic but they vary depending on the type of workstation they are assigned to.
v. Time spent for loading new items to the welding fixture (or station), unloading the processed item from the welding fixture (or station), grasping-releasing the gun/torch and other equipment in-station, moving the item from one station to the next, fixture groups activation/deactivation times are considered as non-value added activities, and those times are subtracted from the workstation gross cycle time.
vi. Product demand is assumed to be deterministic and stationary.
vii. Physical space and budget available for the assembly process are assumed to be sufficient.

The following notation is used in the model:

Sets

$\boldsymbol{N}$ set of station numbers, i.e. N= {1, 2,…, maximum number of stations for a line}

$\boldsymbol{S}$ set of all station types (S=S1 U S2)

$\boldsymbol{S_1}$ set of manual station types

$\boldsymbol{S_2}$ set of robotic station types

$\boldsymbol{T}$ set of all tasks (T=T1 U T2)

$\boldsymbol{T_1}$ set of all tasks except respot welding tasks

T_2 set of respot welding tasks

T_3 set of spot welding tasks

Indexes

t task; $t \epsilon T$

n station; $n \epsilon N$

s station type; $s \epsilon S$

Parameters

CT cycle time (seconds) (set equal to takt time)

mxp maximum number of new parts to load to the welding fixture for the subassembly or assembly line

$prec_{th}$ precedence relations among tasks (when task *t* precedes task *h* , 1; otherwise, 0)

rn_s net number of robot or operators obtained after taking into consideration the inefficiencies because of waiting that occurs when there are more than two operators/robots working in one station and the efficiency ratio determined for manual/robotic stations

pt_{ts} processing time of task *t* in station type *s* (seconds)

cap_{ts} capability of station type *s* to do task *t* (if capable, $cap_{t,s}$=1, otherwise $cap_{t,s}$=0)

ldm_t loading time of new item to the welding fixture in manual station types for task *t* (seconds)

ldr_t loading time of new item to the conveyor in robotic station types for task *t* (seconds)

$fxst_s$ fixed standard time for non-value added activities for station type *s* (seconds)

$conf_{us}$ conformity for consecutive station types in a robotic or manual assembly line (if station type *s* can be positioned right after station type *u*, $conf_{u,s}$ =1; otherwise $conf_{u,s}$=0)

FIP_s annualized total fixed equipment and commissioning cost of station type *s* (€/year)

VM_s annual total fixed operational cost of station type *s* (€/year)

VL_s annual total variable labor cost of station type *s* (€/year)

VD_s annual total variable reworked direct material cost of station type *s* (€/year)

ca_s cost of area occupied by station type *s* (€/year)

v_{ts} annual total variable operating cost if task *t* is processed on station type *s* (€/year)

clro annual total cost of the operator loading items to the conveyor for robotic stations (€/year/operator)

Decision variables

$$x_{tns} = \begin{cases} 1 & if\ task\ t\ is\ performed\ on\ station\ n, of\ type\ s \\ 0 & otherwise \end{cases} \quad for\ t \in T1, n \in N, s \in S$$

$$y_{ns} = \begin{cases} 1 & if\ station\ n\ is\ of\ type\ s \\ 0 & otherwise \end{cases}, for\ n \in N, s \in S$$

r_{tns} : The proportion of respot welding task *t* processed on n^{th} station, which is of type *s*, $for\ t \in T2, n \in N, s \in S$

lro_n : number of operators loading new parts into robotic conveyor lines in n^{th} station, $for\ \ n \in N$

The mixed integer programming model is formulated below.

$$\min\ z = \sum_{n\in N}\sum_{s\in S}(\mathrm{FIP}_s + VM_s + VD_s + VL_s + ca_s).y_{ns} + \sum_{t\in T1}\sum_{n\in N}\sum_{s\in S} v_{ts}.x_{tns} + \sum_{t\in T2}\sum_{n\in N}\sum_{s\in S} v_{ts}.r_{tns} + \sum_{n\in N}(clro).lro_n \tag{5.2}$$

Subject to

$$\sum_{n\in N}\sum_{s\in S} x_{tns} = 1 \qquad \forall t \in T1 \tag{5.3}$$

$$\sum_{n\in N}\sum_{s\in S} r_{tns} = 1 \qquad \forall\, t \in T2 \tag{5.4}$$

$$\sum_{s\in S} y_{ns} \leq 1 \qquad n \in N \tag{5.5}$$

$$x_{tns} \leq cap_{ts} y_{ns} \qquad t \in T1, n \in N, s \in S \tag{5.6}$$

$$r_{tns} \leq cap_{ts} y_{ns} \qquad t \in T2, n \in N, s \in S \tag{5.7}$$

$$\sum_{t\in T1}\sum_{s\in S1} [pt_{ts} + ldm_t].x_{tns} + \sum_{t\in T2}\sum_{s\in S1} pt_{ts}.r_{tns} \leq \sum_{s\in S1} y_{ns}\,.[rn_s.CT - fxst_s] \quad n \in N \tag{5.8}$$

$$\sum_{t\in T1}\sum_{s\in S2} pt_{ts}.x_{tns} + \sum_{t\in T2}\sum_{s\in S2} pt_{ts}.r_{tns} \leq \sum_{s\in S2} y_{ns}\,.[rn_s.CT - fxst_s] \quad n \in N \tag{5.9}$$

$$\sum_{j\in N}\sum_{s\in S} j.x_{tjs} \leq \sum_{k\in N}\sum_{s\in S} k.x_{hks} \qquad t, h \in T1 \text{ and } prec_{th} = 1 \tag{5.10}$$

$$\sum_{j=1}^{n}\sum_{s\in S} r_{hjs} \geq \sum_{s\in S} x_{tns} \qquad t \in T1, h \in T2, n \in N \text{ and } prec_{ht} = 1 \tag{5.11}$$

$$\sum_{j=n}^{|N|}\sum_{s\in S} r_{hjs} \geq \sum_{s\in S} x_{tns} \qquad t \in T1, h \in T2, n \in N \text{ and } prec_{th} = 1 \tag{5.12}$$

$$\sum_{s \in S} y_{n+1,s} \leq \sum_{s \in S} y_{ns} \qquad \forall\, n \; < |N| \tag{5.13}$$

$$\sum_{t \in T3} \sum_{s \in S} x_{tns} \leq mxp \qquad n \in N \tag{5.14}$$

$$\sum_{t \in T3} \sum_{s \in S2} ldr_t . x_{tns} \leq lro_n . CT \qquad n \in N \tag{5.15}$$

$$y_{ns} + \sum_{u \in S} y_{n-1,u} (1 - conf_{us}) \; \leq 1 \qquad s \in S \,, n \in N \text{ and } n > 1 \tag{5.16}$$

$$\begin{aligned} & y_{ns} \in \{0,1\} && \forall\, n, s \quad n \in N, s \in S \\ & x_{tns} \in \{0,1\} && t \in T1, n \in N, s \in S \\ & 0 \leq r_{tns} \leq 1 && t \in T2, n \in N, s \in S \\ & lro_n \geq 0 && n \in N \end{aligned} \tag{5.17}$$

The objective function and the constraints of the model (i.e. equations 5.2 - 5.17) are explained below.

(5.2) The objective is to minimize the total annual cost over the assembly/sub-assembly line, which consists of the fixed equipment and physical area cost for the stations, the variable operating cost that incurs for the tasks to process at the stations, and the cost of operators loading the conveyors at the robotic stations.

(5.3) Each task (except the respot welding task) must be assigned to a single station on the line.

(5.4) A respot welding task can be partially assigned to a station. But for each task, the sum of its portions assigned to the different stations must equal 1, i.e. the task must be completed.

(5.5) Each station on the line can be assigned at most one station type.

(5.6) A task cannot be assigned to a station that has no capability to process it nor to a station which is not open.

(5.7) A respot welding task cannot be assigned to a station that has no capability of respot welding nor to a station which is not open.

(5.8) The sum of the processing and loading times for the tasks assigned to a manual station cannot be greater than the net cycle time determined for that station after taking into consideration the operator inefficiency and time spent for non-value added activities at that station.

(5.9) The sum of the processing times for the tasks assigned to a robotic station cannot be greater than the net cycle time determined for that station after taking into consideration the operator inefficiency and time spent for non-value added activities at that station. Note that the part loading times to robotic station is not considered here, because the loading is done by an outside operator, so the loading time does not reduce the cycle time available for the robotic station.

(5.10) If task *t* is an immediate predecessor of task *h*, then it cannot be assigned to a station with a higher number than the number of station to which task *h* is assigned.

(5.11) This constraint implies that if task *t* is assigned to station *n* (i.e. $\sum_{s \in S} x_{tns} = 1$), then the task *h* which is a predecessor of task *t* must be completed in the stations 1 through *n* (i.e. $\sum_{j=1}^{n} \sum_{s \in S} r_{hjs} = 1$).

(5.12) This constraint implies that if task *t* is assigned to station *n* (i.e. $\sum_{s \in S} x_{tns} = 1$), then the task *h* which is a successor of task *t* must be completed in the stations *n* through the last station |*N*| (i.e. $\sum_{j=n}^{|N|} \sum_{s \in S} r_{hjs} = 1$).

(5.13) The n+1st station cannot be opened if the n^{th} station is not opened.

(5.14) The number of spot welding tasks assigned to a station (i.e. the number of new parts to join) cannot be greater than the pre-defined upper limit.

(5.15) The total loading time required for the spot welding tasks assigned to a robotic station must be less than or equal to the total time available for loading at that station, which is calculated by multiplying the cycle time with the number of operators used for loading parts to that robotic station.

(5.16) If station type s cannot be positioned right after station type u (i.e. $conf_{u,s}$ =0), then if the n^{th} station on the line is of type s, the n-1st station must not be of type u or if the n-1st station is of type u, then n^{th} station must not be of type s.

(5.17) The binary and non-negativity restrictions on the decision variables.

After the model above is solved to optimality, the optimum automation level (AL) is simply calculated as the ratio of the sum of equivalent spot welds of tasks performed in robotic stations to the sum of equivalent sport welds of all tasks multiplied by 100, as indicated below:

$$AL = \left(\frac{\sum_{t \in T_1} \sum_{n \in n} \sum_{s \in S2} ES_t x_{tns} + \sum_{t \in T_2} \sum_{n \in N} \sum_{s \in S2} ES_t r_{tns}}{\sum_t ES_t} \right) x100 \qquad (5.18)$$

Where ES_t represents the equivalent spot welds for task t. Recall that the equivalent spot welds for each task that is not a spot or respot weld task are provided in Table 4.1 in section 4.

6. CASE STUDY

The proposed optimization model is illustrated using real data from an automobile manufacturer in Turkey. The industrial problem considered consists of 21 tasks and 37 equipment alternatives that differ from each other in terms of their capability of doing tasks and task processing times.

6.1 Numerical Data

The *right front rail* is considered as an example for the automation level optimization problem. A schematic view of the assembly of the front rail is shown in Figure 6.1.

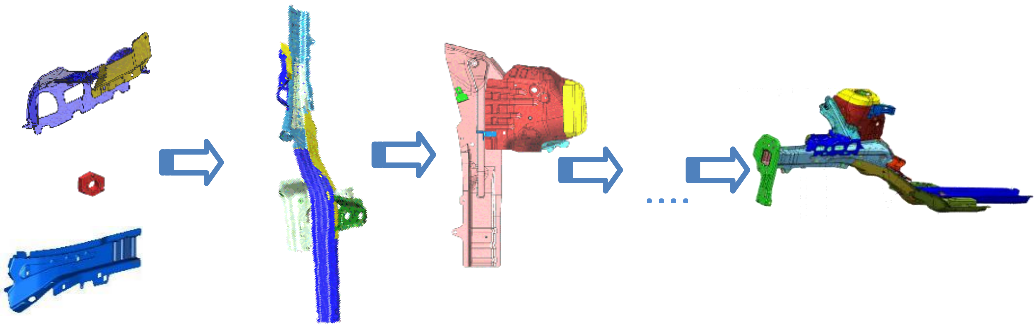

Figure 6.1 Several components of a complete right front rail part

All tasks required for the assembly of right front rail and the alternative station types are explained in this section. For confidentiality reasons, some numerical data (especially, cost values) used for this study cannot be provided here.

6.1.1 Common Parameters

In order to produce a front rail, a number of tasks must be completed on different stations either manually or automatically. Each task consists of a group of some type of welding operations. A task cannot be divided into smaller tasks except for the respot welding task which can be partly assigned to the stations. A complete list of the tasks can be seen in Table 6.1.

Table 6.1 Tasks for the assembly of the right front rail part (*T*)

No	Code	Task	# of weld operation
1	3T01	Task – 1 – Spot Weld	6
2	3T02	Task – 2 – Spot Weld	3
3	3T03	Task – 3 – Spot Weld	6
4	3T04	Task – 4 – Spot Weld	6
5	3T05	Task – 5 – Spot Weld	12
6	3T06	Task – 6 – Spot Weld	3
7	3T07	Task – 7 – Spot Weld	3
8	3K01	Task – 1 – Tucker Weld	1
9	3K02	Task – 2 – Tucker Weld	5
10	3A01	Task – A – Base Material	NA
11	3B01	Task – B – Finished Product	NA
12	3N01	Task – 1 – Nut Weld	2
13	3S01	Task – 1 – Respot Weld	19
14	3S02	Task – 2 – Respot Weld	38
15	3S03	Task – 3 – Respot Weld	22
16	3S04	Task – 4 – Respot Weld	12
17	3G01	Task – 1 – Arc weld (0.154 m)	0.154
18	3D01	Task – D –1– Dummy	NA
19	3D02	Task – D –2– Dummy	NA
20	3Y01	Task – Y –1– Spot Weld	NA
21	3Y02	Task – Y –2– Spot Weld	NA

For example; 3T01 is a spot welding task that includes 6 weld operations. 3G01 is an arc welding task that includes 0.154 meters arc welding operation. 3S02 is a respot welding task that includes 38 spot weld operations. 3N01 is a nut weld task that includes 2 nut weld operations. In Table 6.1, NA represents that no welding operations are performed for the given task, which is a transfer operation from one station to another or from a conveyor to the welding fixture in the workstation. Two dummy operations are included to create a meaningful precedence network diagram, which is shown in Figure 6.2.

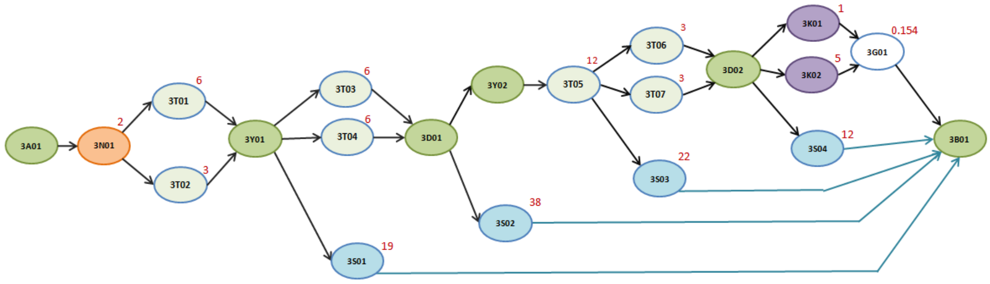

Figure 6.2 Precedence network diagram for the right front rail

The numbers over the task nodes, e.g. 6 over 3T01, symbolizes the number of operations. Based on the precedence relationship network in Figure 6.2, the precedence relationship matrix ($prec_{th}$) is determined, which is shown in Table 6.2. For example, task 3A01 precedes 3N01. Tasks 3T01 and 3T02 are the successors of 3N01. Task 3T05 precedes 3T06, 3T07 and 3S03.

Table 6.2 Precedence relations of the tasks ($\boldsymbol{prec_{th}}$)

Tasks	3A01	3N01	3T01	3T02	3D01	3T03	3T04	3S01	3D02	3S02	3T05	3T06	3T07	3S03	3Y02	3S04	3K01	3K02	3G01	3B01	3Y01
3A01	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3N01	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3T01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
3T02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
3D01	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0
3T03	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3T04	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3S01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
3D02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0
3S02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
3T05	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0
3T06	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
3T07	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
3S03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
3Y02	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
3S04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
3K01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
3K02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
3G01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
3B01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3Y01	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0

All station types and tasks are defined in sets. The sets *T, T1, T2, T3* represent all tasks, all tasks except respot welding tasks, only respot welding tasks, only spot welding tasks, respectively. The sets *S, S1, S2* represent all station types, only manual station types, only robotic station types, respectively. The task-related sets and station type-related sets are provided in Table 6.3 and Table 6.4, respectively.

Table 6.3 Set of tasks (*T, T1, T2, T3*)

T		*T1*		*T2*	*T3*
3A01	3T05	3A01	3N01	3S01	3A01
3N01	3T06	3T07	3K02	3S02	3T01
3T01	3T07	3T06	3K01	3S03	3T02
3T02	3S03	3T05	3G01	3S04	3T03
3D01	3S04	3T04	3D02		3T04
3T03	3K01	3T03	3D01		3T05
3T04	3K02	3T02	3B01		3T06
3S01	3G01	3T01	3Y01		3T07
3D02	3B01		3Y02		3Y01
3S02	3Y01				3Y02
	3Y02				

Table 6.4 Set of station types (*S, S1, S2)*

S			*S1*	*S2*	
M1	R1	R15	M1	R1	R16
M2	R2	R16	M2	R2	R17
M3	R3	R17	M3	R3	R18
M4	R4	R18	M4	R4	R19
M5	R5	R19	M5	R5	R20
M6	R6	R20	M6	R6	R21
M8	R7	R21	M8	R8	R22
M9	R8	R22	M9	R9	
M10	R9		M10	R10	
M11	R10		M11	R11	
M12	R11		M12	R12	
M13	R12		M13	R13	
M14	R13		M14	R14	
M15	R14		M15	R15	

All the tasks must be assigned to a station in the assembly line. However, since each station is equipped with special devices and fixtures, each task may not be performed by any station. In other words, a task cannot be assigned to any station; it must be assigned to a station that is properly equipped to perform this task. The different operations required for the front rail assembly are listed in Table 6.5. The capabilities of manual and robot station types for doing these operations and the equipments used in those station types are provided in Table A.1 and Table A.2, respectively, in Appendix A. For example, M1 is a station type that can perform spot weld operation with one operator using two manual guns on one manual welding fixture and one hoist.

Based on Table A.1, the capability matrix (cap_{ts}) that indicates whether a task t can be performed by station type s is determined, which is provided in Table A.3 of Appendix A. Here "1" indicates that the given station type is able to perform the corresponding task. For example, some station types can perform only spot welding such as station type R1 while some station types can both perform spot welding and load new parts to the workstation such as R2.

Table 6.5 The different operations required for front rail assembly

No	Operations
1	Spot welding
2	New parts loading
3	Get & place WIP
4	Release/transfer WIP
5	Tucker welding
6	Arc welding
7	Nut / screw welding
8	Sealing

In order to configure a reasonable assembly line, each workstation must be ordered serially. In our case the workstation should be compatible with the succeeding workstation as well as the preceding workstation. This case can be considered as plug and socket. The plug of current workstation must be compatible with socket of the preceding or succeeding workstation. So as to make sure this compatibility, a conformity matrix is created, which is given in Table A.4 of Appendix A.

6.1.2 Time Parameters

Each task must be completed within the takt time, which is a gross time for a workstation. The assembly line is planned to operate for 21 hours per day (3 shifts) and 270 days per year ideally without stopping. There is a 30 minute-break time per shift, so each shift is 7.5 hours; the operators are paid considering 22.5 hours per day.

$$takt\ time = total\ available\ time\ for\ production / total\ demand \tag{6.1}$$

For a demand of 200,000 cars per year, the takt time is calculated as:

$$takt\ time = 21\ x\ 270\ x\ 3600\ /200{,}000\ \ = 102.06\ s/car$$

The machines can fail sometimes both in manual and robotic stations. The equipments cannot work with 100% efficiency. Sometimes the failed workstation cause the entire line to stop and sometimes not. A failed machine can cause the failure of consecutive machines. The efficiency rates for manual and robotic stations are set to 93% and 87%, respectively. There may also be two or more human or robot operators working on the same workstation, which also causes some inefficiency. Since the materials are combined by welding operation, robots or operators must work on the part on the welding fixture. In general, the cross-sectional area of the part or the fixing point does not allow two or more operators working simultaneously in the same station, one has to wait for the other finish his part of the work, which causes some idle time. Thus, an operator or a robot can work without being idle if the workstation has only one operator or robot. If two available, idle time ratio is supposed as %5; if three available, idle time ratio is %10; if four available, idle time ratio is %15. After deducting the inefficiency of equipments and idle time of operators or robots, an adjusted number of operators are obtained for each station. This number is denoted as rn_s, which is provided in Table 6.6.

Table 6.6 Inefficiency and idle time-adjusted number of operators (***rn_s***)

station type	# of operators	# of operators multiplied by (1- idle ratio)	Inefficiency & idle time adjusted # of operators
M1	1	1	0.93
M2	2	1.9	1.767
M3	3	2.7	2.511
M4	4	3.4	3.162
M5	1	1	0.93
M6	1	1	0.93
M8	1	1	.93
M9	1	1	0.93
M10	1	1	0.93
M11	1	1	0.93
M12	1	1	0.93
M13	1	1	0.93
M14	1	1	0.93
M15	1	1	0.93
R1	1	1	0.87
R2	1	1	0.87
R3	2	1.9	1.653
R4	2	1.9	1.653
R5	2	1.9	1.653
R6	3	2.7	2.349
R7	3	2.7	2.349
R8	3	2.7	2.349
R9	4	3.4	2.958
R10	4	3.4	2.958
R11	4	3.4	2.958
R12	1	1	0.87
R13	1	1	0.87
R14	1	1	0.87
R15	1	1	0.87
R16	2	1.9	1.653
R17	1	1	0.87
R18	1	1	0.87
R19	1	1	0.87
R20	1	1	0.87
R21	1	1	0.87
R22	1	1	0.87

After the takt time is multiplied by the rn_s number, we obtain the net number of operators or robots in a workstation that is available to perform the tasks. Besides inefficiencies and idle times of the stations, there are also non-value added activities, but essential to perform so as to start or finish a task. Those activities may change according to manual or robotic station depending on both the equipments and the number of operators or robots the workstation has. The fixed non-value added activity time in a workstation, which is performed before an operation starts or after the end of an operation, is listed in Table A.5 of Appendix A. These times are excluded from the takt time after being multiplied by the rn_s, and then the assigned tasks must be finished within the remaining time. If the station is manual, loading time of materials (ldm_t) is also deducted.

The formula to calculate the time available for task processing (TATP) for a station is given as follows

$$TATP\ for\ S = takt\ time\ x\ rn(s) - \ fixed\ nvaa\ time\ for\ S - ldm(t)\quad for\ manual\ st. \tag{6.2}$$

For example, the time available for task processing (TATP) for R1 is calculated as follows

$$TATP\ for\ R1 = 102.06\ x\ 0.87 - 14 = 74.77 s/car$$

If the station were of manual type, we should also deduct the task dependent material loading time to find the TATP for manual stations. A list of task-dependent material loading times (ldm_t) is given in seconds in Table 6.7. For example, getting the 3T01 part from a rack aside of the workstation and placing it to the welding fixture takes 6 seconds.

Loading time to robotic welding fixture is not considered for robotic stations due to its technological configuration, which is supplied by external conveyor system. An additional operator must get and place the materials on the conveyor. The parameter of material loading to robotic station is denoted as ldr_t. This loading time for a conveyor system in robotic station is not deducted from the takt time, but the labor cost incurs for the operator loading the material, so this loading time is incorporated into the model.

Table 6.7 Loading times of new parts to welding fixture in manual stations (***ldm**$_t$*)

Tasks	3A01	3N01	3T01	3T02	3D01	3T03	3T04	3S01	3D02	3S02	
loading times	6	0	6	4	0	7	6	0	0	0	
Tasks	3T05	3T06	3T07	3S03	3Y02	3S04	3K01	3K02	3G01	3B01	3Y01
loading times	7	4	4	0	7	0	0	0	0	0	7

In addition, loading new parts into conveyor in robotic stations is performed outside the operational area. That means the robotic motions are not affected by the loading operations. The time to pick the part from the end of conveyor into the robotic cell is already considered in the parameter $fxst_s$ as non value added time. The number of operator loading new parts to the conveyor is calculated considering the loading times in seconds in Table 6.8.

Table 6.8 Loading times of new parts to conveyor in robotic stations (***ldr**$_t$*)

3T01	3T02	3T03	3T04	3T05	3T06	3T07	3Y01	3Y02	3A01
6	4	7	6	7	4	4	7	7	6

The processing times for welding operations are provided in Table 6.9, for robotic and manual stations.

Table 6.9 Processing time of welding operations manually & robotically

	Processing time (*s*)			
Operation	Manual	Robotic	Unit	Symbol
Spot weld	4.2	2.6	per item	T
Respot weld	3.4	2.3	per item	S
Tucker weld	3.3	3.75	per item	K
Nut weld	6.0	7.5	per item	N
Arc weld	290	350	per meter	G
Sealing	20.8	12	per meter	M
Screw weld	6.0	7.5	per item	V

Processing time for each task is calculated as follows,

$$processing\ time\ T = number\ of\ operation\ x\ manual\ or\ robotic\ time\ of\ operation \tag{6.3}$$

For example, if the task 3N01 that consists of 2 screw welds is performed in a manual station, its processing time is calculated as follows:

$$processing\ time\ \ for\ 3N01 = 2\ x\ 6 = 12\ sec$$

The task processing times for robotic and manual stations are shown in Table A.6 of Appendix A.

6.1.3. Cost Parameters

All cost parameters are calculated annually. Some costs like equipment purchasing cost and area cost are one-time cost that covers the lifespan of the assembly line, which is considered to be 8 years in this study. These kinds of costs are annualized considering the 2% interest rate for euro. The A/P factor for *n*=8 years and *i*=2% is calculated as:

$$A/P\ factor\ = \frac{(\mathrm{i}/100 * (1 + \mathrm{i}/100)\string^\mathrm{n})}{(1 + \mathrm{i}/100)\string^\mathrm{n} - 1)}\ =\ 0.137 \tag{6.4}$$

6.1.3.1. Fixed costs

All the workstations available for the assembly line considered in this study consist of special equipments and devices to do one or more functions as indicated by Table A.1 and Table A.2 in Appendix A. A workstation does not have only robots or operators. In addition, a workstation can have some equipment such as a welding fixture, a manual or robotic gun, a transformer, a hoist and so on. Workstations differ in terms of their capability to perform tasks as well as task processing times. In this study, robotic and manual stations only are considered to perform the tasks of the right front rail assembly. Other types of technological systems are not considered. For example, M3 workstation, which can perform spot welding, new parts loading, get/place WIP and release/transfer

WIP, has an equipment of one welding fixture, three manual guns, three transformers for each gun, one hoist and three operators using each manual gun. All equipments have a fixed cost that is dependent on whether it is manual or robotic. The fixed cost of a workstation is calculated by multiplying the number of equipments by the cost of the corresponding equipment cost plus the commissioning cost, which is 10% of the purchasing cost for manual stations, 15% for robotic stations.

$$Fixed\ Cost\ of\ Equipment = (number\ of\ equipment\ x\ cost\ of\ equipment)\ x\ (1 + commissionning\ rate) \tag{6.5}$$

For example, the fixed cost of M3 workstation is calculated as:

$$Fixed\ Cost\ for\ M3 = (1x30 + 3x5 + 3x10 + 1x4\ )\ x\ 1.1 = 86{,}900\ €/station$$

The annualized fixed cost for this workstation is calculated by multiplying its fixed cost with A/P factor, as shown below.

$$FIP(s) = Fixed\ cost\ of\ equipment\ x\ AP\ factor \tag{6.6}$$

$$FIP(M3) = (1x30 + 3x5 + 3x10 + 1x4\ )x\ 1.1x\ 0.137 = 11863\ €/year$$

Due to the confidentiality reasons, fixed purchasing cost parameters cannot be provided in this document.

The area cost for station type s (ca_s) is calculated by multiplying the space occupied by station s with the unit area cost as well as A/P factor to annualize the cost of area. The unit area cost is 750 €/m^2. Table 6.10 shows the space occupied by each station and the corresponding area cost.

$$cost\ of\ area, CA_s = unit\ space\ cost\ (€/m^2)\ x\ area\ of\ station\ s \tag{6.7}$$

Table 6.10 Area costs for different station types (CA_s)

Station type (s)	Space occupied by station s (m^2)	Area Cost for s (€) (CA_s)
M1	9	921.4
M2	15	1535.7
M3	15	1535.7
M4	19.3	1976.0
M5	9	921.4
M6	9	921.4
M8	6.2	634.8
M9	9	921.4
M10	9	921.4
M11	9	921.4
M12	9	921.4
M13	9	921.4
M14	6.2	634.8
M15	9	921.4
R1	36	3685.8
R2	36	3685.8
R3	72	7371.5
R4	72	7371.5
R5	72	7371.5
R6	90	9214.4
R7	90	9214.4
R8	90	9214.4
R9	110	11262.1
R10	110	11262.1
R11	110	11262.1
R12	25	2559.6
R13	25	2559.6
R14	25	2559.6
R15	30	3071.5
R16	72	7371.5
R17	80	8190.6
R18	50	5119.1
R19	25	2559.6
R20	30	3071.5
R21	30	3071.5
R22	25	2559.6

6.1.3.2. Variable costs

Variable costs are costs that are dependent on the production volume. Generally variable costs increase at a constant rate as the production volume increases. In our study, variable costs include tip cost of manual and robotic guns, electricity cost of equipments when performing welds, electricity cost of equipments when running but not performing welds, compressed air and chilled water cost of equipments, direct operator cost working on the stations, spare parts, cost of reworked direct materials, indirect labor cost like the cost of maintenance and conductor operators, consumable materials such as gloves, safe shoes, uniforms and so on.

The tips are used for robotic and manual welding guns to perform welding operation. The tips are placed at the extremities of gun and sharpened with a device in-station after some usage, then replaced periodically. This is an important part shown in Figure 6.3. If it is replaced later than the normal time it should be replaced, the quality of welding deteriorates, similarly if it is replaced earlier, the cost of tips increases. The cost of this consumable material for manufacturing is identified as variable cost.

Figure 6.3 Tips for welding gun

All variable costs are grouped into specific categories depending on what they are dependent of and the station type. While some costs are demand-dependent, some costs are labor-dependent. However, some costs are variable, but not dependent on demand or labor cost, as long as the machines operate and operators work on workstations, some costs incur annually.

Tip cost of manual and robotic guns, electricity cost of equipments when performing welds, compressed air and chilled water cost of equipments are variable cost dependent on demand. Tip cost is obtained by monitoring the production of existing tools performance. The tip replacement frequency is determined according to the version of the car produced and number of spot welds performed. The cost of tips is also different in sizes and functionalities, rigidity and dependent on station type. Thus, the cost of tip is measured as euro per weld. Electricity cost of equipments when performing welds is measured by current-meter. The consumption of electricity depends also on many parameters, but the average electricity cost per weld is considered. The consumptions of compressed air and chilled water are measured by the counter installed on the machine as it is performed for electricity consumption. Due to confidentiality reasons, the variable costs are not shown in this document, but the real data is used in the study. After observing the existing equipments long time on workstations, the unit variable cost per task *t* in workstation *s* ($\boldsymbol{v_{ts}}$) is calculated.

The cost of reworked direct materials is also dependent on workstation. The rework rate is affected by the number operator or robot in a station, the complexity and technology of the equipments and the speed of the line (or cycle time). This is given to the mathematical model as additional parameter, $\boldsymbol{vd_s}$.

Electricity cost of equipments when running but not performing welds, spare parts cost, consumable materials of operators such as gloves, safe shoes, uniforms etc. are variable costs that are not dependent on demand or labor. They are identified as total operational fixed costs and measured averagely based on past data regarding the equipments, operators and operational cost of produced models in existing lines. All these operational costs are reported as €/station. The parameter is shown as $\boldsymbol{vm_s}$ in the mathematical model.

Direct cost of operator working on the stations, indirect labor cost like the cost of maintenance and conductor operators are all labor dependent cost parameters. Conductor is a term in the plant for a type of technician, whose skill level is in-between maintenance operator and a normal operator. These operators are only serving for robotic stations, thus cost of conductors is incurred in automatic stations. On the other hand, direct operators are only working in manual stations. The parameter is shown as $\boldsymbol{vl_s}$ in the mathematical model.

If a breakdown takes place in a manual station, its repairmen cost is higher than the robotic stations. The historical data shows that the robotic stations fail less than manual stations. The frequency of breakdowns is also important to determine the variable indirect labor cost. The labor cost of stations is calculated as follows

$$Labor\ Cost(s) = (\#\ of\ direct\ and\ indirect\ operator + \#\ of\ conductor)\ x\ cost\ of\ labor \tag{6.8}$$

6.2. Computational Analysis and Results

The proposed mixed integer programming model for this problem is solved using an integer programming solver, CPLEX. The model is coded in GAMS software. The main outputs of the model are the level of automation, total annual cost of the assembly line, the configuration of the line i.e. the workstations and the assignment of tasks to workstations. The results are obtained using CPLEX with the stopping condition set to %0.5 from lower bound. That means that the solution provided deviates from the optimal solution by at most %0.5.

The automation levels obtained for different demand levels and labor cost values are shown in Table 6.11. The results show that the automation level does not change with labor cost when the demand volume is 100,000 units/year. However the automation level increases with labor cost when the demand volume is 150,000 or 200,000 units/year. It is interfered that when the labor cost is at the highest value among the considered scenarios, the automation level has the tendency to increase as the demand increases, but if the labor cost is lower, the automation level does not necessarily increase.

Table 6.11 Automation Level (%) according to different alternatives

Automation Level (%)		Annual Demand		
		100,000	150,000	200,000
Hourly labour cost	2.5 €	37.005	56.740	51.545
	5.0 €	37.005	72.424	69.200
	8.5 €	37.005	72.454	69.200
	26.0 €	37.005	72.454	82.755
	45.0 €	37.005	72.454	82.755

The annual total costs of the assembly line according to different demand volumes and labor costs are shown in the Table 6.12.

The run times of the model according to different demand volumes and labor costs are shown in Table 6.13.

Table 6.12 Annual total cost of the assembly line (€) according to different alternatives

Total Annual Cost (€)		Annual Demand		
		100,000	150,000	200,000
Hourly labour cost	2.5 €	350789.218	555389.486	780237.329
	5.0 €	412338.656	629968.567	895729.713
	8.5 €	498507.869	726455.956	1051382.94
	26.0 €	929353.934	1208892.901	1727115.742
	45.0 €	1397129.661	1732681.584	2450348.858

As a stopping criterion for the solution algorithm, the maximum run time was set to 6000 seconds, but in none of the scenarios the run time reached this limit. The run time seems to be affected significantly by the demand volume. It increases as the demand volume increases. On the other hand, change in labor cost does not seem to affect significantly the run time.

Table 6.13 Run times of the model (seconds) according to different alternatives

Run Time (seconds)		Annual Demand		
		100,000	150,000	200,000
Hourly labour cost	2.5 €	31.937	348.125	2000.797
	5.0 €	17.547	201.875	2688.00
	8.5 €	18.00	151.25	2396.89
	26.0 €	102.234	187.64	1560.00
	45.0 €	106.375	232.485	2069.422

Other important outputs of the model are the configuration of the assembly line, i.e. assignment of tasks to workstations, and the workstation utilization percentage. Some representative results are shown below.

While demand is 200,000 cars per year and labor cost is 8.5 € per hour, Table 6.14 shows the task assignment to workstations, the number of open workstations, the number of working operator or robots and the workstation utilization percentage.

Table 6.14 Workstation details (demand= 200,000; labor cost = 8.5 €)

workstation #	1	2	3	4	5	6
workstation type	M13	M2	M2	R19	R3	R20
3S01		0.055			0.945	
3S02				0.077	0.73	0.193
3S03			0.178	0.822		
3S04					1	
3A01	1					
3N01	1					
3T01	1					
3T02		1				
3D01		1				
3T03		1				
3T04		1				
3D02			1			
3T05			1			
3T06			1			
3T07			1			
3Y02			1			
3K01				1		
3K02				1		
3G01						1
3B01						1
3Y01		1				
# of opr. or robot	1	2	2	1	2	1
usable time	47.1	86.8	88.8	70.7	132.6	70.7
total processing time	37.2	66.6	84.6	70.8	132.7	70.8
workstation load %	79%	77%	95%	100%	100%	100%

While demand is 200,000 per year and labor cost is 5.0 € per hour, the results are shown in Table 6.15.

Table 6.15 Workstation details (demand= 200,000; labor cost = 5.0 €)

workstation #	1	2	3	4	5	6
workstation type	M13	M2	M2	R19	R3	R20
3S01		0.055			0.945	
3S02				0.553	0.254	0.193
3S03			0.178		0.822	
3S04					1	
3A01	1					
3N01	1					
3T01		1				
3T02	1					
3D01			1			
3T03		1				
3T04		1				
3D02			1			
3T05			1			
3T06			1			
3T07			1			
3Y02			1			
3K01				1		
3K02				1		
3G01						1
3B01						1
3Y01		1				
# of opr. or robot	1	2	2	1	2	1
usable time	49.1	84.8	88.8	70.7	132.6	70.7
total processing time	24.6	79.2	88.9	70.8	132.7	70.8
workstation load %	50%	93%	100%	100%	100%	100%

While demand is 200,000 per year and labor cost is 2.5 € per hour, the results are displayed in Table 6.16.

Table 6.16 Workstation details (demand= 200,000; labor cost = 2.5 €)

workstation #	1	2	3	4	5	6
workstation type	M13	M2	M3	R19	R20	R13
3S01		0.345			0.387	0.268
3S02				0.553		0.447
3S03			0.605			0.395
3S04			1			
3A01	1					
3N01	1					
3T01	1					
3T02		1				
3D01			1			
3T03		1				
3T04		1				
3D02			1			
3T05			1			
3T06			1			
3T07			1			
3Y02			1			
3K01				1		
3K02				1		
3G01					1	
3B01						1
3Y01		1				
# of opr. or robot	1	2	3	1	1	1
usable time	47.1	86.8	161.5	70.7	70.7	70.7
total processing time	37.2	85.3	161.7	70.8	70.8	70.8
workstation load %	79%	98%	100%	100%	100%	100%

This time labor cost is fixed to 8.5 € per hour, and the annual demand is varied from 200,000 to 100,000. The results shown in Table 6.17 and Table 6.18, respectively, correspond to annual demand of 150,000 and 100,000. Recall that the results for 200,000 units of annual demand and labor cost of 8.5 € per hour were reported in Table 6.14.

Table 6.17 Workstation details (labor cost = 8.5 €; demand= 150,000)

workstation #	1	2	3	4	5	6
workstation type	M13	M1	M13	R13	R19	R20
3S01						1
3S02				0.972		0.028
3S03					0.994	0.006
3S04					1	
3A01	1					
3N01	1					
3T01	1					
3T02	1					
3D01		1				
3T03		1				
3T04		1				
3D02					1	
3T05			1			
3T06			1			
3T07			1			
3Y02		1				
3K01					1	
3K02					1	
3G01						1
3B01						1
3Y01	1					
# of opr. or robot	1	1	1	1	1	1
usable time	67.7	63.1	75.7	100.3	100.3	100.3
total processing time	49.8	50.4	75.6	85.0	100.4	100.4
workstation load %	74%	80%	100%	85%	100%	100%

Table 6.18 Workstation details (labor cost = 8.5 €; demand= 100,000)

workstation #	1	2	3	4
workstation type	M13	M1	M9	R20
3S01	0.68	0.288	0.032	
3S02				1
3S03			1	
3S04			0.338	0.662
3A01	1			
3N01	1			
3T01	1			
3T02	1			
3D01		1		
3T03		1		
3T04		1		
3D02			1	
3T05		1		
3T06			1	
3T07			1	
3Y02		1		
3K01			1	
3K02			1	
3G01				1
3B01				1
3Y01	1			
# of opr. or robot	1	1	1	1
usable time	131.0	119.4	135.6	159.6
total processing time	93.7	119.4	135.7	159.6
workstation load %	72%	100%	100%	100%

In terms of workstation loads, the optimal solution provided is quite well. Normally it is expected that the workstation load be roughly 90% for robotic stations and 80% for manual stations in industrial practices. The usable time reported in Tables 6.14-6.18 is the net workstation time available to perform the tasks assigned to that workstation.

7. CONCLUSION

We study the problem of determining the optimum automation level for the assembly process at an automobile manufacturer. A mixed integer programming formulation is proposed to determine the appropriate workstation modules that the assembly process should include (i.e. the design of the assembly line) as well as the task assignments to each workstation that satisfy all the system constraints (target production volume, precedence relationship among tasks etc.) while minimizing the total system cost (i.e. sum of operating and investment costs). The optimal automation level is calculated based on the optimal task assignment and workstation types. As an example, the front rail of a commercial vehicle is selected for determining the relevant constraints of the model, while the model can be formulated accordingly for other parts of the vehicle as well. The reasons why the front rail is chosen to illustrate the proposed methodology is that it requires tasks that can be done both manually and using robots and it requires a wide range of system constraints that are also applicable to other parts of vehicle. By solving the proposed mixed integer program for each part of the vehicle separately, and then combining the results, the optimum level of automation required by the vehicle can be calculated.

Numerical experimentation is performed to see the effects of changing demand and labor cost, on the optimum level of automation using real data from an automobile manufacturing company in Turkey. Results show that the automation level is non-decreasing as the labor cost increases for a fixed demand volume. On the other hand, when labor cost is fixed, an increase in demand may lead to a decrease in automation level.

As further work, the proposed model can be extended to incorporate dynamic demand over the planning horizon. Another interesting work would be to analyze how the automation level would be affected in the existence of limited budget and storage space.

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APPENDIX A: Inputs of the Case Study

Table A.1 Capability of manual station types

MANUAL STATIONS	CAPABILITY								ROBOT	NUTS-SCREW EQUIPMENT+APPARAT (MANUAL)	NUTS-SCREW EQUIPMENT (ROBOTIC)	CO_2 MACHINE manual	CO_2 MACHINE robotic	CONVEYOR	FIXED GUN	ROBOTIC GUN	GRIPPER	APPARAT	TUCKER MACHINE (=power unit)	TUCKER GUN & FEEDER	SEALING EQUIPMENT	MANUAL GUN	TRANSFORMER	TOOL CHANGER	TRACK	CARASKAL	OPERATOR	AREA (m2)
	spot Weld	new parts loading	get & place WIP	release / transfer WIP	tucker welding	arc welding	nut / screw welding	sealing																				
M1	x	x	x	x														1				2	1			1	1	9.0
M2	x	x	x	x														1				4	2			1	2	15.0
M3	x	x	x	x														1				3	3			1	3	15.0
M4	x	x	x	x														1				4	4			1	4	19.3
M5		x	x	x		x						1						1								1	1	9.0
M6	x	x	x	x		x						1						1				1	1			1	1	9.0
M8		x	x	x	x													1	1	2							1	6.2
M9	x	x	x	x	x													1	1	2		1	1			1	1	9.0
M10	x	x	x	x				x										1			1	1	1			1	1	9.0
M11		x	x	x				x										0			1						1	9.0
M12		x	x	x			x			1								0									1	9.0
M13	x	x	x	x			x			1								1				1	1			1	1	9.0
M14		x	x	x	x													0	1	2							1	6.2
M15		x	x	x		x						1						0									1	9.0

Table A.2 Capability of robotic station types

ROBOTIC STATIONS	CAPABILITY: spot Weld	new parts loading	get & place WIP	release / transfer WIP	tucker welding	arc welding	nut / screw welding	sealing	ROBOT	NUTS-SCREW EQUIPMENT+APPARAT (MANUAL)	NUTS-SCREW EQUIPMENT (ROBOTIC)	CO_2 MACHINE manual	CO_2 MACHINE robotic	CONVEYOR	FIXED GUN	ROBOTIC GUN	GRIPPER	APPARAT	TUCKER MACHINE (=power unit)	TUCKER GUN & FEEDER	SEALING EQUIPMENT	MANUAL GUN	TRANSFORMER	TOOL CHANGER	TRACK	CARASKAL	OPERATOR	AREA (m2)
R1	x								1							1		1										36.0
R2	x	x							1					1		1	1	1						1				36.0
R3	x								2							2		1										72.0
R4	x	x							2					1		2	1	1						1				72.0
R5	x	x							2					2		2	2	1						2				72.0
R6	x								3							3		1										90.0
R7	x	x							3					1		3	1	1						1				90.0
R8	x	x							3					2		3	2	1						2				90.0
R9	x								4							4		1										110.0
R10	x	x							4					1		4	1	1						1				110.0
R11	x	x							4					2		4	2	1						2				110.0
R12			x	x					1								1											25.0
R13	x		x	x					1						1		1											25.0
R14			x	x				x	1								1				1							25.0
R15	x		x	x				x	1						1		1				1							30.0
R16	x	x						x	2					2		2	2	1			2			2				72.0
R17			x	x	x				1								1	1	1	2								80.0
R18			x	x		x			1				1				1											50.0
R19	x		x	x	x				1						1		1		1	2								25.0
R20	x		x	x		x			1				1		1		1											30.0
R21	x		x	x			x		1		1				1		1											30.0
R22			x	x			x		1		1						1											25.0

Table A.3 Capability matrix of alternative workstations (***cap***$_{ts}$)

	M1	M2	M3	M4	M5	M6	M8	M9	M10	M11	M12	M13	M14	M15	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19	R20	R21	R22
3A01	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
3N01	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
3T01	1	1	1	1	0	1	0	1	1	0	0	1	0	0	0	1	0	1	1	0	1	1	0	1	1	0	0	0	0	1	0	0	0	0	0	0
3T02	1	1	1	1	0	1	0	1	1	0	0	1	0	0	0	1	0	1	1	0	1	1	0	1	1	0	0	0	0	1	0	0	0	0	0	0
3D01	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
3T03	1	1	1	1	0	1	0	1	1	0	0	1	0	0	0	1	0	1	1	0	1	1	0	1	1	0	0	0	0	1	0	0	0	0	0	0
3T04	1	1	1	1	0	1	0	1	1	0	0	1	0	0	0	1	0	1	1	0	1	1	0	1	1	0	0	0	0	1	0	0	0	0	0	0
3S01	1	1	1	1	0	1	0	1	1	0	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1	0	1	0	1	1	0	0	1	1	1	0
3D02	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
3S02	1	1	1	1	0	1	0	1	1	0	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1	0	1	0	1	1	0	0	1	1	1	0
3T05	1	1	1	1	0	1	0	1	1	0	0	1	0	0	0	1	0	1	1	0	1	1	0	1	1	0	0	0	0	1	0	0	0	0	0	0
3T06	1	1	1	1	0	1	0	1	1	0	0	1	0	0	0	1	0	1	1	0	1	1	0	1	1	0	0	0	0	1	0	0	0	0	0	0
3T07	1	1	1	1	0	1	0	1	1	0	0	1	0	0	0	1	0	1	1	0	1	1	0	1	1	0	0	0	0	1	0	0	0	0	0	0
3S03	1	1	1	1	0	1	0	1	1	0	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1	0	1	0	1	1	0	0	1	1	1	0
3Y02	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1
3S04	1	1	1	1	0	1	0	1	1	0	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1	0	1	0	1	1	0	0	1	1	1	0
3K01	0	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
3K02	0	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
3G01	0	0	0	0	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0
3B01	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1
3Y01	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1

Table A.4 Conformity matrix of alternative workstations (***conf**$_{us}$*)

	M1	M2	M3	M4	M5	M6	M8	M9	M10	M11	M12	M13	M14	M15	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19	R20	R21	R22
M1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1
M2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1
M3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1
M4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1
M5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1
M6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1
M8	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1
M9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1
M10	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1
M11	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1
M12	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1
M13	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1
M14	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1
M15	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1
R1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1
R2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1
R3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1
R4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1
R5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1
R6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1
R7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1
R8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1
R9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1
R10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1
R11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1
R12	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1
R13	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1
R14	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1
R15	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1
R16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R17	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1
R18	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1
R19	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1
R20	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1
R21	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1
R22	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1

Table A.5 Non value added activity times on each workstation (***fxst***$_s$)

# of operator & robots	station type	fxst(s)	non value added activities in station / unit act.time (min)	Reset the welding fixture (AS)	Closing groups (GK)	Opening groups (GA)	Get the gun (PA)	Release the gun (PB)	Get the torch (TA)	Release the torch (TB)	Get the tucker gun (TTA)	Release the tucker gun (TTB)	Get the sealing gun (MTA)	Release the sealing gun (MTB)	Transfer time inbetween stations	Idle time to get the completed WIP (TPAB)	Idle time to place the completed WIP (YPKB)	Closing groups (GK)	Opening groups (GA)	Change of gripper or gun (GPD)	Get new parts from conveyor (YPA)	Load new parts to welding fixture (YPAY)	Get the part from previous workstation (BÖİPA)	Place the part to next station (BSIPB)
				2.4	5.4	5.4	4.2	3.4	4.5	3.4	2.6	2.6	2.3	1.6	15	7	7	2	2	14	7	7	10	8
1	M1	43.4		2.4	5.4	5.4	8.4	6.8							15									
2	M2	69.4		2.4	10.8	10.8	16.8	13.6							15									
3	M3	72.6		2.4	16.2	16.2	12.6	10.2							15									
4	M4	91.0		2.4	21.6	21.6	16.8	13.6							15									
1	M5	36.1		2.4	5.4	5.4			4.5	3.4					15									
1	M6	43.7		2.4	5.4	5.4	4.2	3.4	4.5	3.4					15									
1	M8	38.6		2.4	5.4	5.4					5.2	5.2			15									
1	M9	46.2		2.4	5.4	5.4	4.2	3.4			5.2	5.2			15									
1	M10	39.7		2.4	5.4	5.4	4.2	3.4					2.3	1.6	15									
1	M11	18.9											2.3	1.6	15									
1	M12	15.0													15									
1	M13	35.8		2.4	5.4	5.4	4.2	3.4							15									
1	M14	25.4									5.2	5.2			15									
1	M15	22.9							4.5	3.4					15									
1	R1	18.0														7	7	2	2					
1	R2	44.0																	2	28	7	7		
2	R3	36.0														14	14	4	4					
2	R4	76.0																2	4	42	14	14		
2	R5	88.0																	4	56	14	14		
3	R6	54.0														21	21	6	6					
3	R7	108.0																4	6	56	21	21		
3	R8	120.0																2	6	70	21	21		
4	R9	72.0														28	28	8	8					
4	R10	140.0																6	8	70	28	28		
4	R11	152.0																4	8	84	28	28		
1	R12	18.0																					10	8
1	R13	18.0																					10	8
1	R14	18.0																					10	8
1	R15	18.0																					10	8
2	R16	88.0																	4	56	14	14		
1	R17	18.0																					10	8
1	R18	18.0																					10	8
1	R19	18.0																					10	8
1	R20	18.0																					10	8
1	R21	18.0																					10	8
1	R22	18.0																					10	8

Table A.6 Processing time of tasks in both manual and robotic workstations (***pt_{ts}***)

# of operations	Tasks	M1	M2	M3	M4	M5	M6	M8	M9	M10	M11	M12	M13	M14	M15
0	3A01	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	3N01	12	12	12	12	12	12	12	12	12	12	12	12	12	12
6	3T01	25.2	25.2	25.2	25.2	25.2	25.2	25.2	25.2	25.2	25.2	25.2	25.2	25.2	25.2
3	3T02	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6
0	3D01	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	3T03	25.2	25.2	25.2	25.2	25.2	25.2	25.2	25.2	25.2	25.2	25.2	25.2	25.2	25.2
6	3T04	25.2	25.2	25.2	25.2	25.2	25.2	25.2	25.2	25.2	25.2	25.2	25.2	25.2	25.2
19	3S01	64.6	64.6	64.6	64.6	64.6	64.6	64.6	64.6	64.6	64.6	64.6	64.6	64.6	64.6
0	3D02	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	3S02	129.2	129.2	129.2	129.2	129.2	129.2	129.2	129.2	129.2	129.2	129.2	129.2	129.2	129.2
12	3T05	50.4	50.4	50.4	50.4	50.4	50.4	50.4	50.4	50.4	50.4	50.4	50.4	50.4	50.4
3	3T06	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6
3	3T07	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6
22	3S03	74.8	74.8	74.8	74.8	74.8	74.8	74.8	74.8	74.8	74.8	74.8	74.8	74.8	74.8
0	3Y02	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	3S04	40.8	40.8	40.8	40.8	40.8	40.8	40.8	40.8	40.8	40.8	40.8	40.8	40.8	40.8
1	3K01	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
5	3K02	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5
0.154	3G01	44.66	44.66	44.66	44.66	44.66	44.66	44.66	44.66	44.66	44.66	44.66	44.66	44.66	44.66
0	3B01	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	3Y01	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A.6 Processing time of tasks in both manual and robotic workstations ($\boldsymbol{pt_{ts}}$) (cont.)

# of operations	Tasks	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12
0	3A01	0	0	0	0	0	0	0	0	0	0	0	0
2	3N01	15	15	15	15	15	15	15	15	15	15	15	15
6	3T01	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6
3	3T02	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8
0	3D01	0	0	0	0	0	0	0	0	0	0	0	0
6	3T03	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6
6	3T04	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6
19	3S01	43.7	43.7	43.7	43.7	43.7	43.7	43.7	43.7	43.7	43.7	43.7	43.7
0	3D02	0	0	0	0	0	0	0	0	0	0	0	0
38	3S02	87.4	87.4	87.4	87.4	87.4	87.4	87.4	87.4	87.4	87.4	87.4	87.4
12	3T05	31.2	31.2	31.2	31.2	31.2	31.2	31.2	31.2	31.2	31.2	31.2	31.2
3	3T06	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8
3	3T07	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8
22	3S03	50.6	50.6	50.6	50.6	50.6	50.6	50.6	50.6	50.6	50.6	50.6	50.6
0	3Y02	0	0	0	0	0	0	0	0	0	0	0	0
12	3S04	27.6	27.6	27.6	27.6	27.6	27.6	27.6	27.6	27.6	27.6	27.6	27.6
1	3K01	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75
5	3K02	18.75	18.75	18.75	18.75	18.75	18.75	18.75	18.75	18.75	18.75	18.75	18.75
0.154	3G01	53.9	53.9	53.9	53.9	53.9	53.9	53.9	53.9	53.9	53.9	53.9	53.9
0	3B01	0	0	0	0	0	0	0	0	0	0	0	0
0	3Y01	0	0	0	0	0	0	0	0	0	0	0	0

Table A.6 Processing time of tasks in both manual and robotic workstations ($\boldsymbol{pt_{ts}}$) (cont.)

# of operations	Tasks	R13	R14	R15	R16	R17	R18	R19	R20	R21	R22
0	3A01	0	0	0	0	0	0	0	0	0	0
2	3N01	15	15	15	15	15	15	15	15	15	15
6	3T01	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6
3	3T02	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8
0	3D01	0	0	0	0	0	0	0	0	0	0
6	3T03	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6
6	3T04	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6
19	3S01	43.7	43.7	43.7	43.7	43.7	43.7	43.7	43.7	43.7	43.7
0	3D02	0	0	0	0	0	0	0	0	0	0
38	3S02	87.4	87.4	87.4	87.4	87.4	87.4	87.4	87.4	87.4	87.4
12	3T05	31.2	31.2	31.2	31.2	31.2	31.2	31.2	31.2	31.2	31.2
3	3T06	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8
3	3T07	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8
22	3S03	50.6	50.6	50.6	50.6	50.6	50.6	50.6	50.6	50.6	50.6
0	3Y02	0	0	0	0	0	0	0	0	0	0
12	3S04	27.6	27.6	27.6	27.6	27.6	27.6	27.6	27.6	27.6	27.6
1	3K01	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75
5	3K02	18.75	18.75	18.75	18.75	18.75	18.75	18.75	18.75	18.75	18.75
0.154	3G01	53.9	53.9	53.9	53.9	53.9	53.9	53.9	53.9	53.9	53.9
0	3B01	0	0	0	0	0	0	0	0	0	0
0	3Y01	0	0	0	0	0	0	0	0	0	0

BIOGRAPHICAL SKETCH

Yusuf GÜNEY was born in Artvin on February 14, 1983. He graduated from Artvin High School in 2001. He received a B.Sc. degree in Industrial Engineering from Marmara University in 2006. His undergraduate senior project was on assembly line balancing. Since July 2007, he has been working as a senior engineer in a private company. He wrote his thesis under the supervision of Asst. Prof. Dr. S.Şebnem AHISKA in the Master of Science program in Industrial Engineering at Galatasaray University. He published the following paper based on his MS thesis work.

Yusuf Guney, S.Sebnem Ahiska, Automation level optimization for an automobile assembly line, Proceedings of the 2014 Industrial and Systems Engineering Research Conference, IIE Annual Conference and Expo, Montreal, Canada, May 31 - June 3, 2014.