DOKUZ EYLUL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

FACILITY LAYOUT USING WEIGHTED ASSOCIATION RULE-BASED DATA MINING ALGORITHMS: EVALUATION WITH SIMULATION

by

Serkan ALTUNTAŞ

August, 2010

İZMİR

FACILITY LAYOUT USING WEIGHTED ASSOCIATION RULE-BASED DATA MINING ALGORITHMS: EVALUATION WITH SIMULATION

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M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"FACILITY LAYOUT USING WEIGHTED ASSOCIATION RULE-BASED DATA MINING ALGORITHMS: EVALUATION WITH SIMULATION"** completed by **SERKAN ALTUNTAŞ** under supervision of **ASST.PROF.DR. HASAN SELİM** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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FACILITY LAYOUT USING WEIGHTED ASSOCIATION RULE-BASED DATA MINING ALGORITHMS: EVALUATION WITH SIMULATION

ABSTRACT

This thesis addresses facility layout problem. Facility layout has considerable effects on the operational productivity and efficiency of a facility because of its direct effect on material handling costs. The objective of this study is to propose new weighted association rule based-data mining approaches for facility layout problem. Classic association rule-based approaches assume that each item has the same level of significance. On the other hand, in weighted association rule-based approaches, each item is assigned a weight according to its significance with respect to some user defined criteria.

In this study, different weighted association rule-based data mining approaches, namely MINWAL(O), MINWAL(W), WARM and BWARM, are applied to the facility layout problem. To address the needs in practice, “demand”, “part handling factor” and “efficiency of material handling equipment” are used as the weighting criteria. Then, this study differs from the previous works in that it considers the three key location factors together. Also, this is the first study that applies weighted association rule-based data mining approaches to the facility layout problem. To confirm the viability of the proposed approaches, two case studies are presented. The approaches are compared in terms of general performance criteria for the facility layout problems using simulation.

Keywords: Weighted Association Rule, Data Mining, Facility Layout, Simulation

AĞIRLIKLI İLİŞKİLENDİRME KURALLARINA DAYALI VERİ MADENCİLİĞİ ALGORİTMALARINI KULLANARAK TESİS YERLEŞİMİ: SİMÜLASYON İLE ANALİZ

ÖZ

Bu tezde tesis yerleşimi problemi ele alınmıştır. Malzeme taşıma maliyetlerine olan direkt etkisi nedeniyle tesis yerleşiminin üretim sisteminin verimliliği ve etkinliği üzerinde önemli etkileri vardır. Bu tezin amacı, tesis yerleşim probleminin çözümüne yönelik olarak ağırlıklı ilişkilendirme kuralları tabanlı yeni veri madenciliği yaklaşımları önermektir. Klasik ilişkilendirme kuralı tabanlı yaklaşımlar her ürünün önem düzeyinin aynı olduğu varsayımına dayanmaktadır. Ağırlıklı ilişkilendirme kurallarında ise her ürünün kullanıcı tarafından tanımlanmış kriterlere göre belirlenen önem düzeyini ifade eden bir ağırlık değeri vardır.

Bu çalışmada MINWAL(O), MINWAL(W), WARM ve BWARM adlı farklı ağırlıklı ilişkilendirme kuralları tesis yerleşimi problemine uygulanmıştır. Gerçek hayattaki ihtiyaçları dikkate alarak, ağırlıklandırma kriterleri olarak “ürün talebi”, “ürün aktarma faktörü” ve “ürün aktarma ekipmanın etkinliği” kullanılmıştır. Böylece, bu çalışma bu üç anahtar yerleşim faktörünü birlikte dikkate alması yönüyle daha önceki ilgili çalışmalardan farklılaşmaktadır. Ayrıca bu çalışma, ağırlıklı ilişkilendirme kuralları tabanlı veri madenciliği yaklaşımlarını tesis yerleşim problemine uygulayan ilk çalışmadır. Çalışmada geliştirilen yaklaşımların uygulanabilirliğini doğrulamak amacıyla iki vaka çalışması sunulmuştur. Ele alınan yaklaşımlar tesis yerleşimi problemlerinde dikkate alınan genel performans kriterleri açısından simülasyon kullanılarak karşılaştırılmıştır.

Anahtar Kelimler: Ağırlıklı İlişkilendirme Kuralları, Veri Madenciliği, Tesis Yerleşimi, Simülasyon

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CHAPTER ONE
INTRODUCTION

1.1 Introduction to Facility Layout Problem

Enterprises have to make improvements in production processes to decrease their product costs and to increase their productivity. The activities in manufacturing systems that do not add value to the products, such as "waiting time in queue" and "flow time of materials", can be reduced or eliminated through improvements in production processes. Tompkins et al. (1996) indicate that 20 to 50 percent of the total operating expenses are composed of material handling costs and an effective facility layout can reduce these costs by at least 10% to 30%.

Facilities are very important resources for manufacturing systems because of their costs. Facility layout can be considered as a decision making problem dealing with which facility will be located to which area in a production system. Facility layout is related to locating or positioning facility/facilities in order to optimize (maximize or minimize) at least one objective function (like cost, profit, revenue, travel distance, service level, waiting time and market shares) (Farahani, Seifi , and Asgari, 2010). Therefore, it has a vital importance for efficient utilization of available machines, workers and workspace.

Machines are important resources for manufacturing systems, and their locations have direct effects on efficiency and productivity of these systems. The location and arrangement of machines can be considered as a typical facility layout problem. From this perspective, facility layout problem deals with the question of where m numbers of machines (each with area a_i) are arranged within a given location. The aim of the location and arrangement of machines in the manufacturing system is to find related machines. The significant problem of facility layout is about the decision on which pairs of facilities should be located next to each other (Wäscher and Merker, 1997). The most related machines are located adjacent to each other as possible so as to minimize transfer time, waiting time in queue, product cycle time, and maximize total production and machine utilization. Machine location is a very important problem for manufacturers because of their effects on ergonomic production as well as efficiency and productivity.

Hassan (1994) indicates that machine layout affects the material handling cost and time, throughput and productivity of the facility and some factors, namely material handling system used, available space, the similarity of the sequences of operations of the parts, the capability of meeting system's requirements. He also reports that other factors related to production and product characteristics affect the machine layout.

Facility layout problem can be classified into three types: 1) static facility layout problem (SFLP), 2) dynamic facility layout problem (DFLP) and 3) stochastic facility layout problem. The following sections provide a brief overview of these problems.

1.1.1 Static Facility Layout Problem (SFLP)

Static facility layout problem deals with the question of where m numbers of machines/departments (each with area a_i) are arranged within a given location when there is no variability in product demand between periods. Jithavech (2008) indicates that material handling cost is one of the most commonly used performance measures and the objective function in SFLP approach aims to minimize the total material handling cost while maximizing the closeness ratio. We have to adjacently locate the machines which are related to each other the most to obtain optimum value of this objective function. As Afentakis, Millen, and Solomon, (1990) define, this problem involves finding which processing modules should be adjacent to each other and how they should be connected with the transfer links of the material handling system to minimize the material handling requirements. To find out more about SFLP, the readers can refer to Kusiak and Heragu (1987) and Meller and Gau (1996).

1.1.2 Dynamic Facility Layout Problem (DFLP)

Dynamic facility layout problem deals with the question of where *m* numbers of machines/departments (each with area a_i) are arranged within a given location when there is variability in product demand from one period to next. Afentakis et al. (1990) state that if the performance of manufacturing system is decreased to 36%, relayout strategy occurs when compared to the best strategy. On the other hand, relayout adds cost to manufacturing expenses because of moving of the machines to new locations (Ulutas, 2008). Interested readers can refer to Koren et al. (1999) to find out more about dynamic facility layout problem.

1.1.3 Stochastic Facility Layout Problem

Stochastic facility layout problem deals with the question of where *m* numbers of machines/departments (each with area a_i) are arranged within a given location when there is stochastic product demand. Stochastic facility layout problem is called “static” when there is no variability in product demand between periods and “dynamic” when there is variability in product demand from one period to next. The influence of demand uncertainty on facility layout may be more important when there is a quick changing customer requirement. The main aim of stochastic facility layout problem is to reflect changing product demand to facility layout to minimize the total material handling cost and to maximize the adjacencies (closeness) of machines that are most related to each other. For more information, interested readers can refer to Krishnan, Jithavech and Liao,(2009) and Snyder (2006).

1.1.4 Research Problem

There are two types of approaches for solving facility layout problem. These are; procedural and algorithmic approaches. Procedural approaches take into account qualitative and quantitative criteria. On the other hand, most of the proposed algorithmic approaches in literature only take into account quantitative criteria, except few studies (Yang and Hung, 2007; Yang and Kou, 2003) which use multi-criteria decision making technique. One of the well known procedural approaches is systematic layout planning (SLP) proposed by (Muther, 1973). Two different types of algorithmic algorithms exist for facility layout problem, namely *constructive type algorithms* and *improvement type algorithms* (Edwards, Gillett and Hale, (1970); Scriabin and Vergin, 1975; Domschke and Krispin, 1997). Constructive type algorithms do not need any initial layout. Therefore, they are used when a layout is developed for the first time. Constructive type algorithms consist of two main stages. The first stage responds to which machine to be assigned with which order to facility layout. The second stage responds to which machine to be located with which area in facility layout. PLANET (Plant Layout Analysis and Evaluation Technique), CORELAP (COmputerized RElationship LAyout Planning) and ALDEP (Automated Layout Design Program) can be given as examples for constructive type algorithms. On the other hand, improvement type algorithms need an initial layout to improve that layout. These type algorithms employ an exchange procedure the result of which produce the best solution than previous layouts (Heragu and Kusiak, 1998). COFAD (COmputerised Facilities Design) and CRAFT (Computerized Relative Allocation of Facilities Technique) are the two examples for the improvement type algorithms.

In this thesis, five new constructive type algorithms that are based on weighted association rule are proposed for static facility layout problem.

1.1.5 Research Objective

The main objective of this thesis is to propose weighted association rule-based algorithms for static facility layout problem. The proposed algorithms are based on weighted association rule-based data mining algorithms, namely MINWAL(O), MINWAL(W), WARM and BWARM. The proposed algorithms are intended to maximize the adjacencies of machines. To address the needs in practice, “demand”, “part handling factor” and “efficiency of material handling equipment” are used as the weighting criteria. Then, this study differs from the previous works in that it considers the three key location factors together.

Abdou and Dutta (1990) claim that facility layout is generally affected by the demand quantity of products. Additionally, Chan, Chan and Ip, (2002) indicate that facility layout is impacted by part-handling factor, which is related to the shape, size and the weight of the products. For this factor, minimum value represents the most difficult way of transporting the parts and maximum value represents the easiest way of transporting between machines. On the other hand, material handling is related to move of a material from one place to another place. There may be some factors that affect the efficiency of equipment used for material handling during this move between departments or machines. These are location of departures, position of product handling, product quantity and speed of equipment used for material handling etc. There may be various material handling equipments in production systems. Some material handling equipments work faster or slower related to part-handling factor. For example, the transport speed of the conveyor can be slow down compared with normal transport speeds if the weight of product is too much. Sule (1994) indicates that from 30 to 75 percent of the total operating expenses in manufacturing are attributed to material handling costs and efficient material handling could reduce these costs by 15 to 30 percent.

In our computational experiments, presented in Chapter Four, we employ Analytical Hierarchy Process (AHP) to weight machines using their “demand”, “part handling factor” and “efficiency of material handling equipment” factors.

1.2 Introduction to Data Mining in Manufacturing

Han and Kamber (2001) define data mining as the process of extracting or “mining” knowledge from large amounts of data. According to the Roiger and Geatz (2003), the aim of data mining methods is to identify trends and patterns in data. Data mining, which is an interdisciplinary field, based techniques are used in a wide range of topic in the literature such as marketing, computer science, manufacturing systems etc. These techniques are decision trees, clustering rules, neural networks, classification, association rule etc. Interested readers can refer to Choudhary, Harding, and Tiwari, (2009) to find out more about data mining in manufacturing. Some of the most widely used data mining techniques in manufacturing systems are described in the following.

1.2.1 Clustering

Clustering refer to the collecting similar items in the same cluster. As Vercellis (2009) state, the aim of clustering models is to subdivide the records of a dataset into homogeneous groups of observations, called *clusters*, so that observations belonging to one group are similar to one another and dissimilar from observations included in other groups. The items are clustered based on the principle of maximizing the intraclass similarity and minimizing the interclass similarity (Han and Kamber, 2001). Clustering models have long been used in various disciplines, such as social sciences, biology, astronomy, statistics, image recognition, processing of digital information and marketing.

1.2.2 Classification

Classification is a popular data mining technique. Some items/records can be classified based on their specific attributes. Each items/records are assigned to one class. The items/records in each class resemble to each other according to the specific attributes. Dunham (2003) indicates that applications of classification method includes medical diagnosis, image and pattern recognition, loan approval, detecting faults in industry application, and classifying financial market trends. Classification method frequently employs decision tree or neural network-based classification algorithms (Sumathi and Sivanandam, 2006). Vercellis (2009) indicates the purpose of classification as follows:

> "*The purpose of a classification model is to identify recurring relationships among the explanatory variables which describe the examples belonging to the same class. Such relationships are then translated into classification rules which are used to predict the class of examples for which only the values of the explanatory attributes are known. The rules may take different forms depending on the type of model used*".

1.2.3 Association Rules

Association rules are used to find relationship among items. The typical application of association rule is market basket analysis. When we purchase product A in market and if purchasing of product A ensures the purchase of product B, we can say that "there is a relationship between product A and product B". Therefore, market sales can be increased when we located product A and product B close to each other as possible. Managers of market can use association rules to increase their profit. As Dunham (2003) states, association rules are frequently used by retail stores to assist in marketing, advertising, floor placement, and inventory control.

There are two main formulas to determine the relationship among items. These are "support" and "confidence". The support value for association rule of products {A→B} is calculated as follows: ({A→B} means that it is highly probable that if A exists in the transaction, B will also be exists in the same transaction).

support {A→B}= P(A∩B) = (number of transactions containing both A and B) / (total number of transactions)

The confidence value for association rule of products {A→B} is calculated as follows.

confidence {A→B}= P(B\A) = (number of transactions containing both A and B) / (number of transactions containing A)

Herein, a small example is given to show the calculation of support and confidence values. Sample data to illustrate association rules is presented in Table 1.1.

Table 1.1 Sample data to illustrate association rules

Transaction	Items
t_1	A, B, C
t_2	B, C
t_3	A, C

Here, there are six different associations among items. These are; {A→B}, {B→A}, {A→C}, {C→A}, {B→C}, and {C→B}. The selection of association rules is based on support and confidence value. Minimum support and minimum confidence values are determined by decision makers. Decision makers determine the minimum values by their expectations. Herein, we determine the minimum support and minimum confidence values as 67%. The association of {A→C}, {C→A}, {B→C}, and {C→B} can be accepted as relationship because only these associations provide the minimum support and confidence values. For instance, consider {A→C} in Table 1.2, with confidence 100%. This indicates that if A occurs, so does C. In other words, 100% of time that A is occurred in transaction, so is C. This is a stronger association than {A→B} because its confidence value is less than the association of {A→C}. Support indicates the percentage of time the association rule occurs throughout the database. For example, consider {B→A} in Table 1.2. Here, the confidence is 50% but the support is only 33%. It may be the case that this association rule exists only in 33% of transactions.

Table 1.2 Support and confidence for 2-level association rules

{X→Y}	Support (%)	Confidence (%)
{A→B}	33	50
{B→A}	33	50
{A→C}	67	100
{C→A}	67	67
{B→C}	67	100
{C→B}	67	67

Figures 1.3, 1.4 and 1.5 illustrate the linkage and correlation between data mining and manufacturing systems. Bolded lines show stronger links. Figures 1.3 shows the linkage and correlation between manufacturing area and data mining techniques. It can be seen from Figure 1.3 that the techniques employed most in manufacturing systems are hybrid technique for job shop and quality control related data, neural network for manufacturing processes related data and association rules for product design related data. Figure 1.4 illustrates the correlation and linkage between data mining functions and manufacturing area. As can bee seen from the figure, classification for quality control, association for product design, prediction for manufacturing process and concept description for job shop are most highlighted linkages between data mining functions and manufacturing area. Additionally, Figure 1.5 shows the linkages between knowledge area, mining functions and techniques. One of the most highlighted linkages is the one between cluster, hybrid and maintenance. Similarly, there is a stronger linkage between product design and association function. Choudhary et al. (2009) claim that association rule based data mining algorithms have generally been used for product design, process control, mass customization, cellular design etc.

As mentioned previously, one of the main data mining methods is association rule, the aim of which is to find the correlation between items. Hipp, Guntzer and Nakhaeizadeh (2000), Zhao and Bhowmick (2003) and Kotsiantis and Kanellopoulos (2006) can be referred for more details on the association rules.

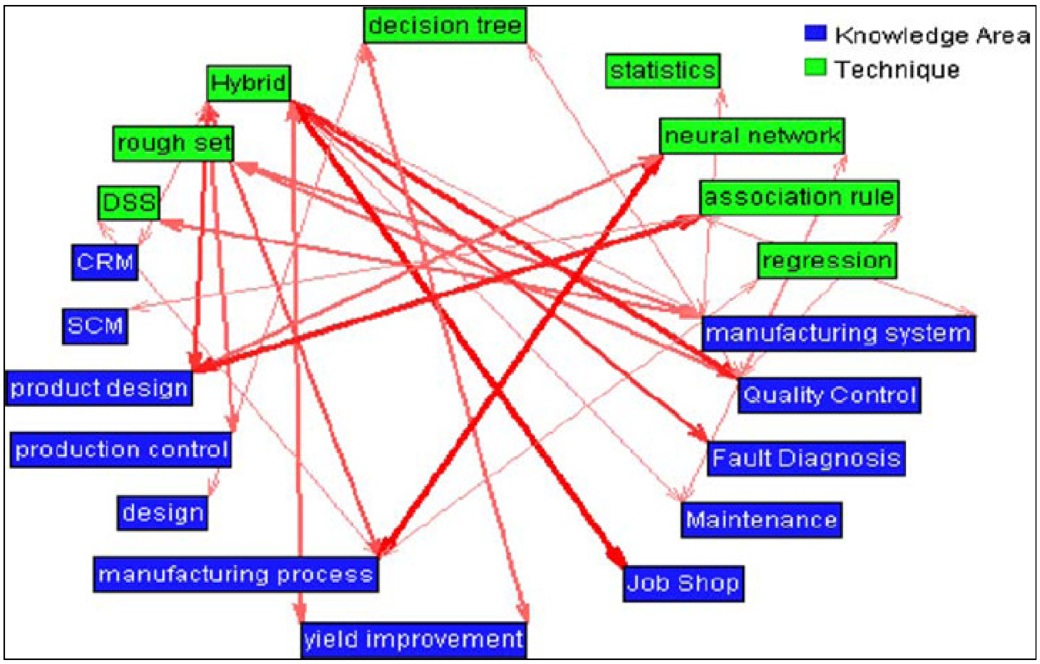


Figure 1.3 Linkage and correlation between manufacturing area and data mining techniques (Choudhary et al., 2009)

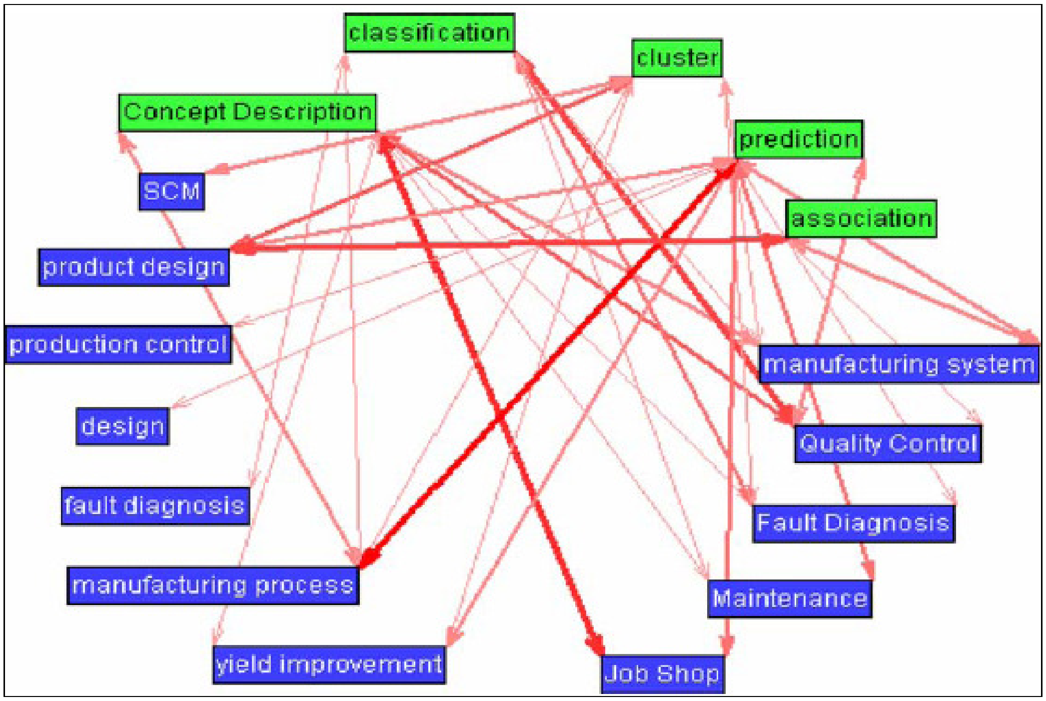


Figure 1.4 Correlation and linkage between data mining functions and manufacturing area (Choudhary et al., 2009)

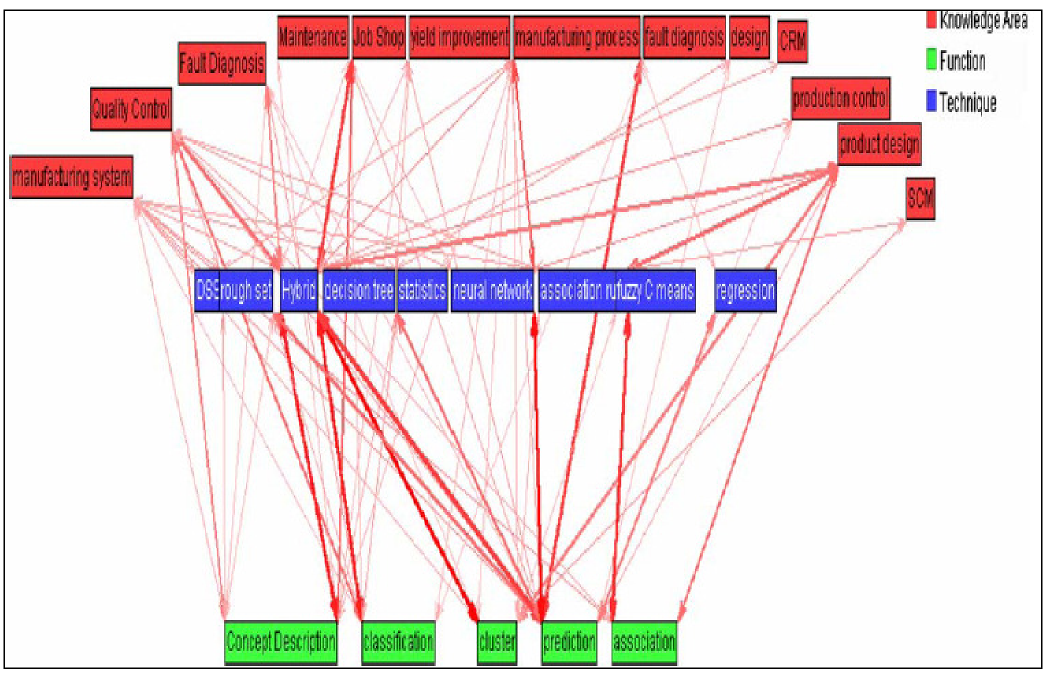


Figure 1.5 Linkages between knowledge area, mining functions and techniques (Choudhary et al., 2009)

1.3 Introduction to Association Rules with Weighted Items

Classic association rules, which are introduced in Section 1.2.5, assume that each item has the same level of significance. Therefore, there is no superiority of items to each other. But in practice, some items may be more important than others. Therefore, decision makers have to reflect this importance level to the items. That is, each item in weighted association rule is assigned a weight by considering the significance of the criteria defined by the decision makers. The weights may be related to the special promotions on some products or the profitability of different items. Factors that affect real-life problems can be easily considered in the model by finding the association between items by using weighted association rules. We can assign any value, within the bound 0 and 1, to any type of the item(s). This value shows the importance level of the item(s). The following example is given for better understanding the differences between classic association rule and weighted association rule.

Example rules:
X: [apple → bananas, 20% (support value), 90% (confidence value)]
Y: [tomato → cherry, 35% (support value), 90% (confidence value)]

In classic association rule, Y is more important than X because support value of rule Y is higher. However, in weighted association rule, rule X may be more important than rule Y, even though X holds a lower support value. This is because those items in the first rule usually may come with more profit per unit sale, but the classic association rule ignores this difference.

1.4 Organization of the Research

The remainder of the thesis is organized as follows. In Section 2, we review the literature related to the implementation of data mining in manufacturing systems. Additionally, weighted association rule-based studies are mentioned. Furthermore, facility layout problem and association rule-based approaches in facility layout problems are explained in Section 2. The proposed weighted association rule-based approaches are introduced in Section 3. In this concern, MINWAL(O)-Based Approach, MINWAL(W)-Based Approaches, WARM-Based Approach and BWARM-Based Approach are presented. Section 4 is devoted to the presentation of the computational experiments aiming the illustration of the viability of the proposed approaches. To this aim, two case studies with different size are handled in Section 4. Finally, Section 5 presents conclusion and future research directions.

CHAPTER TWO
LITERATURE REVIEW

2.1 Implementation of Data Mining in Manufacturing Systems

Kusiak (2006) reviews the applications of data mining in manufacturing and service systems and outlined a framework for decision making based on the knowledge provided by different data mining algorithms. The author states that the proposed data mining approaches involve two phases: learning and decision-making, makes data mining suitable for system-on-a-chip applications. Harding, Shahbaz, Srinivas, and Kusiak, (2006) reviews applications of data mining in manufacturing engineering, in particular production processes, operations, fault detection, maintenance, decision support, and product quality improvement. Customer relationship management, information integration aspects, and standardization are also briefly discussed in the study. Shahbaz, Srinivas, Harding, and Turner Shahbaz (2006) examine the application of association rules to manufacturing databases to extract useful information about a manufacturing system's capabilities and its constraints. The research is based on the belief that the explicit knowledge and information extracted from existing data warehouses, or from current product and production processes, can be used to improve the performance of manufacturing systems. Choudhary et al. (2009) claim that there is great amount of applications of data mining based algorithms in manufacturing, including quality control, scheduling, maintenance, assembly, materials planning etc. Additionally, Ismail, Othman, and Bakar (2009) review the application of data mining in production planning and scheduling.

2.2 Weighted Association Rule-Based Studies

In this section, the various approaches and methodologies used for weighted association rules are presented. Cai, Fu, Cheng, and Kwong, (1998)'s paper is the pioneering study on weighted association rules. They generalize the classical association rules, and introduce a new rule, namely weighed association rule. The items of the database are given weights to reflect their importance to the user. They proposed new algorithms to mine weighted binary association rules. Two algorithms, namely MINWAL(O) and MINWAL(W) are designed for this purpose.

Lu, Hu, and Li (2001) propose the vertical and mixed weighted association rules. The rules can divide the database into several time intervals, and assign a weight for each interval. They present an algorithm MWAR (Mixed Weighted Association Rules) to handle the problem of mining mixed weighted association rules.

Tao, Murtagh, and Farid, (2003) propose a new algorithm called WARM (Weighted Association Rule Mining) for discovering significant relationships between items. WARM algorithm is based on transition weight, and a weight is attached to each of the transitions.

Zhou, Wu, Zhang, Chen, and Zhang (2007) implement a fast and stable algorithm to mining weighted association rules base on the open source library Lucene. The methods to create an index in Lucene and utilization of this index to find weighted frequent itemsets are introduced in the study.

Yun (2007) introduces a w-confidence measure and the concept of weighted affinity patterns by the w-confidence. The main goal of the study is to detect correlated patterns with high weight and/or support affinity patterns by pushing the w-confidence and the original h-confidence into the pattern growth method.

Jiang, Zhao, Yang, and Dong (2008) propose an algorithm for mining the positive and negative weighted association rules with multiple minimum supports. They extend the existing association rule model to allow the user to specify multiple minimum supports to reflect different natures and/or frequencies of items. Specifically, the algorithm allows the user can specify a different minimum item support for each item. Zhu and Xu (2008) present an efficient algorithm (PNAR) for mining both positive and negative association rules in databases. The algorithm extends traditional association rules to include negative association rules. PNAR generates not only all positive association rules in frequent itemset (NL) but also negative association rules in NL. Ramaraj and Venkatesan (2008) focus on a new algorithm called BitArrayNegativePos that mines both positive and negative rules from the real time surveyed medical database. The algorithm shows usage of sparse matrix to mine association rules with bit array data structure.

Jian and Ming (2008) investigate to find the efficiency of communication alarm correlation analysis. Items appearing in transactions are weighted using AHP to reflect the importance of them which is more meaningful in some applications. They implement a fast and stable algorithm to mine weighted association rules based on item sequence sets.

Yue, Tsang, Yeung, and Shi (2000) define the weighted support and weighted confidence for fuzzy association rules. They use the Kohonen self-organized mapping to fuzzify the numerical attributes into linguistic terms. The authors develop a new fuzzy association rules mining algorithm, which generalizes the popular Apriori Gen large itemset based algorithm. Wang and Zhang (2003) put forward the mining algorithm for a set of fuzzy weighted frequent pattern and the algorithm for generating rules. Mining fuzzy weighted association rules have two stages, 1) generate a frequent itemset L in which the support ratio of all members is higher than minsup, 2) produce the wanted association rules by taking advantage of L. Bin, Min, and Bo (2005) propose the problem of mining weighted generalized fuzzy association rules with fuzzy taxonomies (WGF-ARs). The leaf-node items and ancestor items are assigned weights to reflect their correlative importance to the user in their WGF-ARs. Kaya and Alhajj (2006a) propose Genetic Algorithms (GAs) based clustering method, which dynamically adjusts the fuzzy sets to provide maximum profit based on user specified linguistic minimum support and confidence terms to solve the problem of interval partitioning. The approach uses two different fitness functions. As one of them deals with the maximum number of large itemsets based on linguistic minimum support, the other employs the average of the confidence intervals of the rules. Kaya and Alhajj (2006b) address the fuzzy weighted multi-cross-level association rule mining. They define a fuzzy data cube, which facilitates for handling quantitative values of dimensional attributes, and hence allows for mining fuzzy association rules at different levels. They also propose a mining algorithm for extracting interesting fuzzy rules in a given taxonomy. They use three important criteria, minimum support, minimum confidence and item importance, in determining the interestingness of the rules represented by fuzzy sets. Kaya and Alhajj (2006c) develop a novel approach for online fuzzy weighted association rules mining. The proposed method handles the mining process in multidimensional fuzzy data cube. Then, they integrate the multiple-level and weighting concepts with the proposed method. Khan, Muyeba, and Coenen (2008) present a novel approach for mining weighted association rules (ARs) from binary (BWARM) and fuzzy (FBWARM) data. They generalize the weighted association rule mining problem for databases with binary and quantitative attributes with weighted settings. Kaya and Alhajj (2008) address the integration of fuzziness with On-Line Analytical Processing (OLAP), which is one of the most popular tools for on-line, fast and effective multidimensional data analysis, based association rules mining. They present three methods for fuzzy weighted association rules mining within a single dimension, multiple dimensions and hybrid that combine the other two.

Sun and Bai (2008) introduce a new measure w-support, which does not require pre assigned weights. It takes the quality of transactions into consideration using link-based models. First, the HITS model and algorithm are used to derive the weights of transactions from a database with only binary attributes. Based on these weights, a new measure w-support is defined to give the significance of item sets. It differs from the traditional support in taking the quality of transactions into consideration. Then, the w-support and w-confidence of association rules are defined in analogy to the definition of support and confidence.

Li and Hailin Xiao (2007) study the algorithms of weighted association rules mining and weights confirming in alarm correlation analysis. They propose a novel method named Neural Network based WFP-Tree (NNWFP) for mining association rules. In the weights generation, the weights can reflect the importance of the alarms with the neural network. The main portions of NNWFP algorithm include WFP-tree construction and weighted association rules mining.

Mei and Zhu (2008) present the weighted model in the incremental mining algorithm and proposed risk analysis of the strong association rules for trend forecasting. The paper emphasizes the risk degree of the lost association rules; thereby it improves the significance of incremental mining and supports the decision-making.

Yun (2008) proposes weighted frequent pattern mining with length decreasing support constraints. The proposed approach is to push weight constraints and length decreasing support constraints into the pattern growth algorithm. For pruning techniques, the paper proposes the notion of the Weighted Smallest Valid Extension (WSVE) property with/without Minimum Weight (MinW). The WSVE property with/ without MinW is applied to transaction pruning, node pruning and path pruning to eliminate weighted infrequent patterns earlier.

Ge, Qiu, Chen, and Yin (2008) adapt traditional model of association rule mining problems where each item is allowed to have a weight. They use typical association rules mining algorithm to propose an improved weighted association rules mining for information push algorithm that available to information push. The goal is to steer the mining focus to those significant relationships involving items with significant weights rather than being flooded in the combinatorial explosion of insignificant relationships.

Forsati and Meybodi (2010) propose three algorithms to solve the web page recommendation problem. In their first algorithm, they use distributed learning automata to learn the behavior of previous users' and recommend pages to the current user based on learned patterns. By introducing a novel weighted association rule mining algorithm, they present their second algorithm for recommendation purpose. Also, a novel method is proposed in the paper to pure the current session window. They present a hybrid algorithm based on distributed learning automat and propose weighted association rule mining algorithm to improve the efficiency of first two algorithms.

Dua, Singh, and Thompson (2009) present a novel method for the classification of mammograms using a unique weighted association rule based classifier. Association rules are derived between various texture components extracted from segments of images and employed for classification based on their intra- and inter-class dependencies. They also presented a novel framework for the weighting of the rules based on rule presence in different classes to employ intra- class and inter-class similarities.

2.3 Facility Layout Problem

Many numbers of efforts have been done to address the facility layout problem and a number of approximate or heuristic approaches are proposed in the literature. Among these studies, Brandeau and Chiu (1989), (Current, Min, and Schilling, 1990)), (Meller and Gau, 1996), (Canen and Williamson, 1998), (Drira, Pierreval, Hajri-Gabouj, 2007), Singh and Sharma (2006) and Farahani et al. (2010) review different approaches in the literature for facility layout problem. Snyder (2006) reviews the literature on stochastic and robust facility location models. Marcoux, Riopel, and Langevin (2005) present models and methods for facility layout design from applicability to real-world perspective. Liggett (2000) reviews different approaches for automated facility layout and evaluates these approaches. Domschke and Krispin (1997) give basic definition and some solution approaches for location and layout planning.

Herein, some important studies on SFLP are mentioned briefly. Koopmans and Beckman (1957) develop quadratic assignment problem for SFLP. Armour and Buffa (1963) present a new methodology based on quadratic integer programming. Foulds and Robinson (1976) develop a branch and bound algorithms for obtaining an optimal solution. General solution approaches for layout problems are given in Figure 2.1.

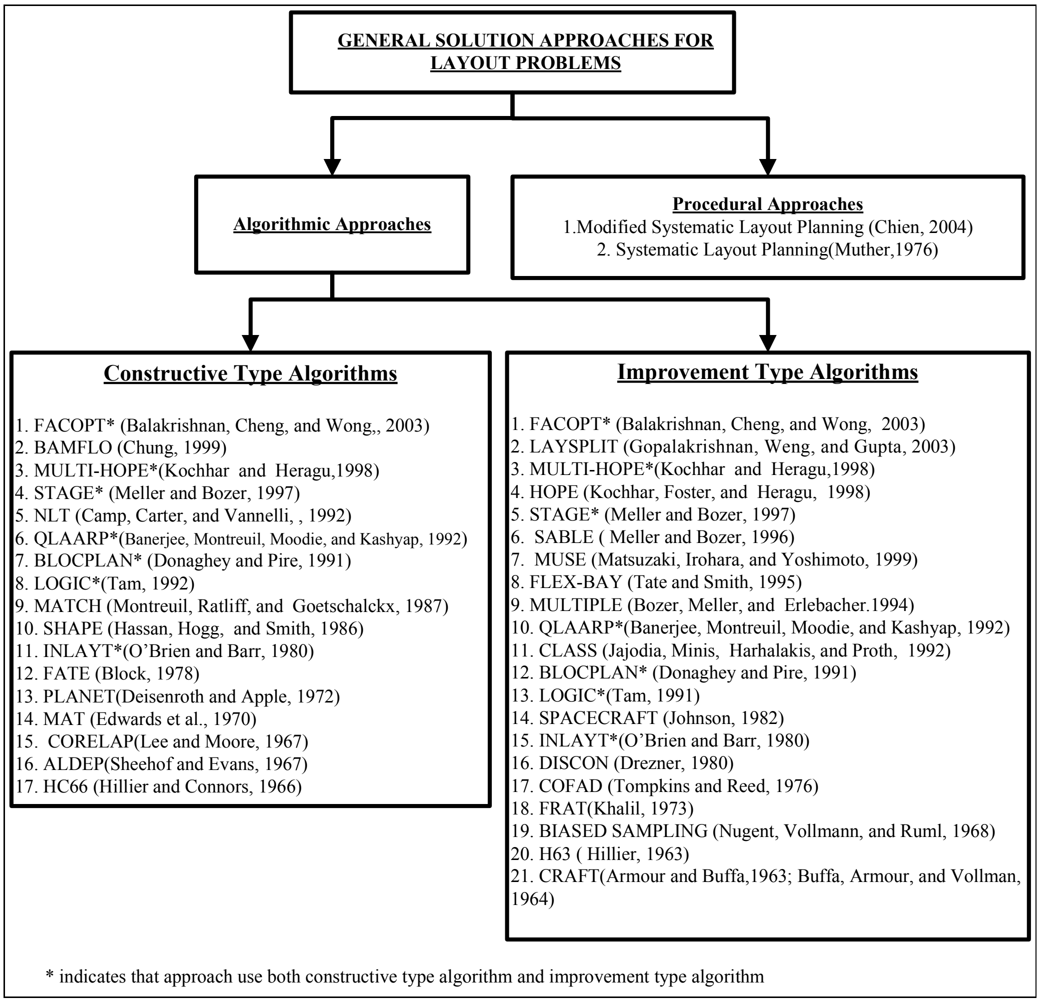


Figure 2.1 General solution approaches for layout problems

As can be seen from Figure 2.1, most of the proposed approaches are algorithmic approaches. A lot of different technologies such as genetic algorithm, simulated annealing, taboo research, fuzzy logic, dynamic programming, etc. are used to research effective procedural and algorithmic approach (Chien, 2004).

2.4 Association Rule-Based Approaches in Facility Layout Problem

The number of studies on the application of association rules to facility layout problem is very limited. Chen (2003) develops a cellular manufacturing system by using association rule mining. He finds relationship between machines from the process database by inducting association rules. The algorithm determines the group of machine in cells. After the formation of machines in cells is completed, the algorithm proceeds to assign each part to machine cells. Mahamaneerat, Shyu, Ho, and Chang (2007) propose a novel domain-concept association rules (DCAR) mining algorithm for complex cell formation problems which consist of a non-binary machine-component matrix, product demand, bill of material, cost and maximum number of machines allowed to each cell. The aim of DCAR algorithm is to minimize inter-cell material movement and intra-cell void element cost as well as to maximize the grouping efficiency. Liu, Yasuda, Yin, and Tanaka (2009) claim that Chen (2003)'s approach ignores many real-life production factors. Therefore, they develop a data mining algorithm which takes some real-life production factors into account such as operation sequence, production volume, cell size, batch size, alternative process routings, number of cells and path coefficient of material flows for the cell formation problem in the cellular manufacturing system.

2.5 Conclusion

As mentioned above, no previous work applies weighted mining association rules to manufacturing systems although there exist several studies that apply classic association rules in this area. To fill this gap, we propose five new weighted association rule-based mining algorithms for the facility layout problem in this study.

CHAPTER THREE
PROPOSED APPROACHES

The proposed weighted association rule-based mining algorithms are based on the algorithms developed by Cai et al. (1998), Tao et al. (2003) and Khan et al. (2008), respectively.

3.1 MINWAL(O)-Based Approach

Basic definitions related to the proposed approach are presented in the following. Weighted Machine: Given a set of machines (A=I1, I2, . . . , In), we assign a weight, wj (where 0<wj<1), for each machine. To reflect their importance, machines are weighted using a relevant method.

- Transition (T): Each product route is referred to as transition. Total number of products in the production system considered in this study equals to the total number of transition.

- Machineset: A set of machines is referred to as machineset. A machineset that contains *k* machines is called k- machineset. For example, the set{*M*1, *M*2, *M*3} is a 3-machineset.

- wminsupport: weighted minimum support which is specified by the decision maker. Magnitude of wminsupport is between 0 and 1.

- Support Count(X) (*SC(X)*): Number of transition containing machineset/machine *X*. When we count the number of transition for a machineset, we only take adjacent machineset into account.

- Maximum possible weight for any *k*-machineset containing machine *Y (W(Y,k)*): Let *D* be the set of all machines. Suppose that *Y* is a *q*-machineset, where $q < k$. In the set of the remaining items (*D-Y*), let the machines with the (*k-q*) greatest

- weights ir_1, ir_2, ir_3,…, ir_{k-q}. We can say that the maximum possible weight for any k-itemset containing machine Y is

$$W(Y,k) = \sum_{i_j \in Y} w_j + \sum_{i_j \in Y}^{k-q} w_{r_j} \tag{1}$$

where, the first statement is the sum of the weights for the q-machinesets Y, and the second statement is the sum of the $(k - q)$ maximum remaining weights.

- k-support bound of Y: the minimum count for a large k-machinesets containing Y is given by

$$B(Y,k) = ((wminsup*T) / W(Y,k)) \tag{2}$$

We called this k-support bound of Y. Using the value of second equation we determine an upper bound for $B(Y,k)$ since it should take an integer value.

The result of the second equation means that if the k-machineset is the subset of any large k+1-machinesets, the count of the k-machineset must be greater than or equal to the result of the second equation.

- Size: Maximum possible large weighted machinesets in production system. The number of size is equal to k. We determine the number of size using all routes of the products. The number of machines of a product which route has maximum number of machines is equal to the number of size.

- Join: C_x is a candidate weighted machinesets. We generate C_x from C_{x-1} by joining (C_{x-1}). Two (x-1)-machinesets will join together to form a x-machineset, with the condition that the first (x-2)-machines of (x-1)-machinesets are equal. For example, if we have {1,2,4,6} and {1,2,7,8} in C_{k-1}, {1,2,4,6,7,8} will be generated in C_x.

- Prune: A machineset will be pruned by Prune(C_x), in either of the following cases:
  Rule (i). If support count Y is not equal or bigger than x-support bound of Y.

Rule (ii). A subset of candidate machineset in C_x does not exist in C_{x-1}.

The solution of facility layout problem consists of two main stages. The first stage responds to which machine to be assigned with which order to facility layout. The second stage responds to which machine to be located with which area in facility layout. The proposed MINWAL(O)-based approach can be structured in two stages when implementing to the facility layout problem. Figure 3.2 illustrates the first stage, while Figures 3.1 and 3.3 illustrate stage 2. We use the algorithm in Figure 3.3 to locate the machines among which there exists an association. Then, if there exists a machine set among which there are not any associations, we use the algorithm in Figure 3.2 to order these machines for allocation.

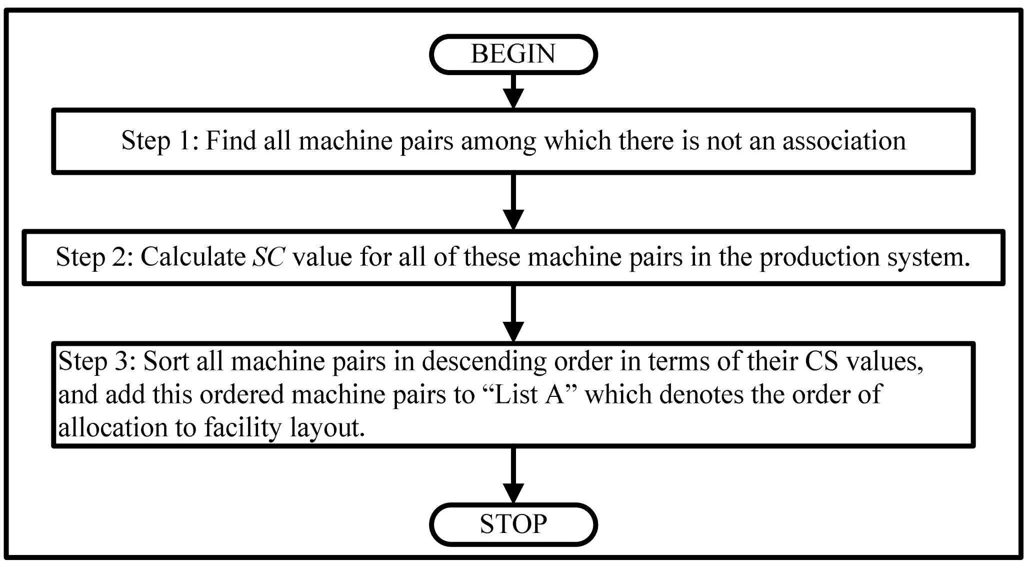


Figure 3.1 Flow algorithm for the machines having no associations

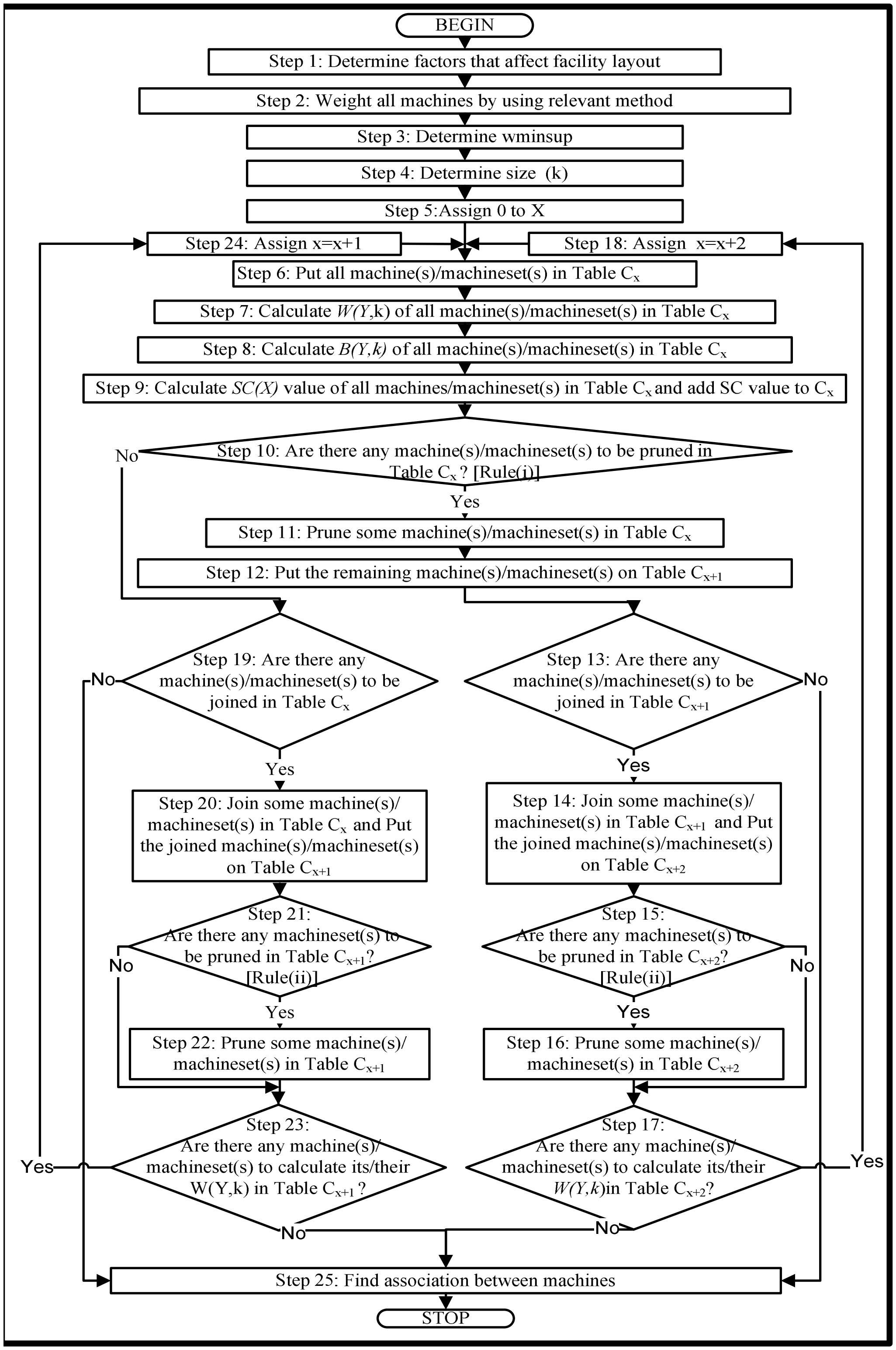


Figure 3.2 The algorithm of the proposed MINWAL (O)-based approach to find association between machines

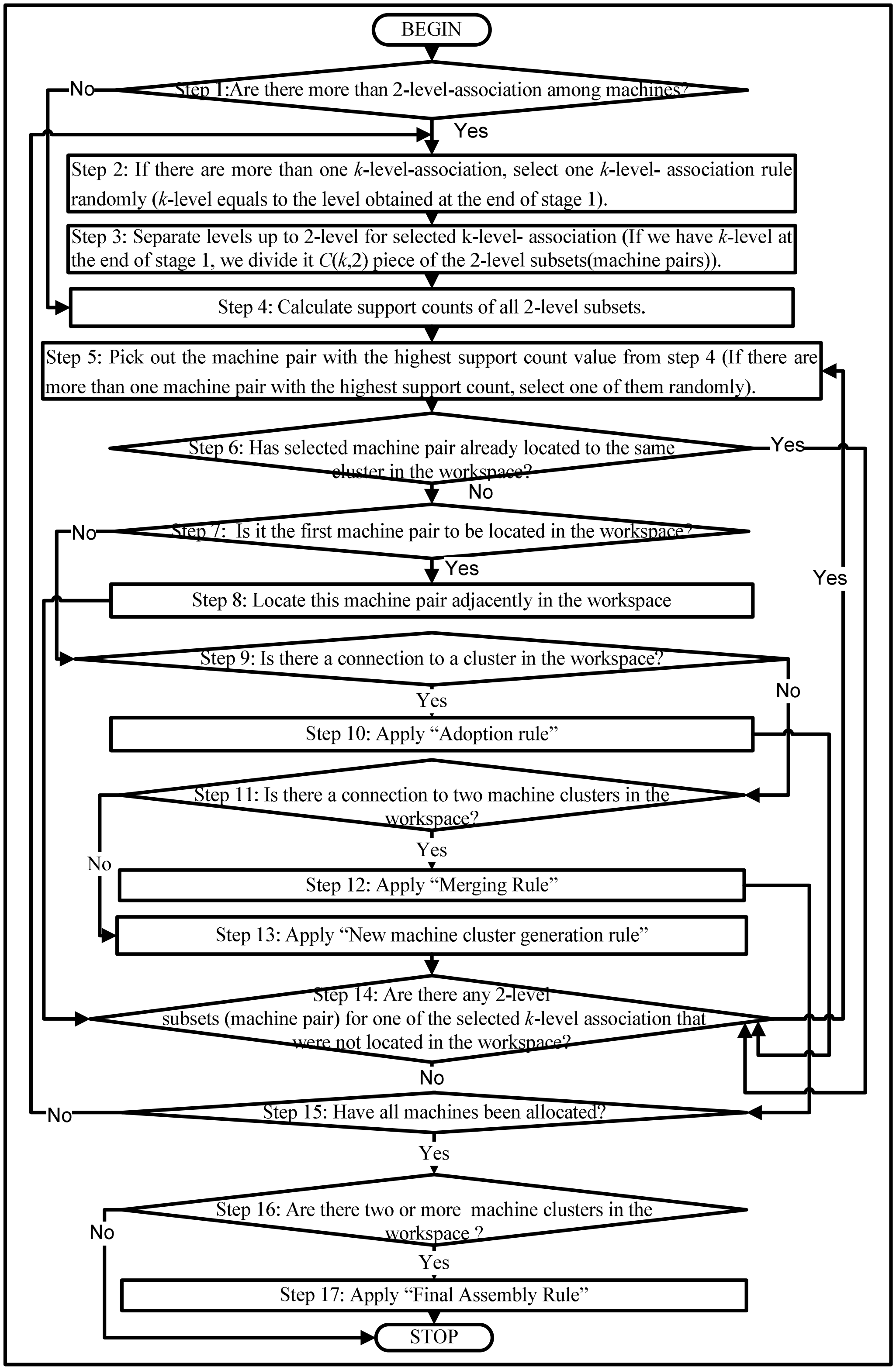


Figure 3.3 Location algorithm of the proposed MINWAL(O)-based approach

There may be some special situations when we assign machine pairs to facility layout. This is because there exist some flexibility in placing the current machine pair. In this study, we apply four rules to assign machine pairs to facility layout. The first three of them, “New machine cluster generation rule”, “Adoption rule” and “Merging Rule”, are proposed by Chan et al. (2002), and the last one, “Final Assembly Rule” is proposed by us. Details of these four rules are presented in the following:

- New machine cluster generation rule**:** If the selected machine pair has no connection to the existing cluster(s) in the workspace, we assign this machine pair a new temporary workspace. This new workspace will be merged with the other workspace in the future. There may be more than one temporary workspace during machine location but final facility layout will be single.

- Adoption rule: If the selected machine pair has a connection to a cluster in the workspace, the selected machine pair is allocated adjacent to this cluster. The aim of adoption is to allocate machine pairs, which have connection to each other, close to each other.

- Merging Rule: If the selected machine pair has connection to two machine clusters in the workspace, we combine these two clusters into one cluster. When we merge two machine clusters, we have to allocate machine pair adjacently.

- Final Assembly Rule: If all of the machines are located in the workspace and there is more than one cluster, these clusters are combined into one cluster to obtain final facility layout. In combining the clusters, one cluster is determined as the main cluster. The main cluster can be selected by counting the number of machines in each cluster. The cluster including the biggest number of machine is selected as the main cluster. If the number of machine in each cluster is equal, the cluster which first machine pair is located on is selected as the main cluster. The other clusters called temporary clusters. Starting from the first machine pair which is located to create the temporary clusters, we locate machine pairs to appropriate locations in the main cluster. The machines in the temporary clusters will be located to the main cluster until all of the machines in the temporary clusters are depleted. Finally, we obtain a single cluster which is called “final facility layout” by applying *final assembly rule*.

Herein, a small example is given to point out the details of these four rules. Eight machines are considered in the example. The association between machines and the order of machine location are given in Table 3.1, while the workspace is illustrated in Table 3.2.

Table 3.1 The Association between machines

The order of location	Association between machines
1	{7,8}
2	{1,2}
3	{2,3}
4	{6,7}
5	{1,4}
6	{2,4}
7	{3,4}
8	{5,6}
9	{6,4}
10	{9,10}

Table 3.2 The Workspace

Firstly, machine pair {7, 8} is located

7	8

Second, machine pair {1,2} is located to facility layout. Since machine pair {1,2} has no connection to the first cluster in the workspace, we assign this pair to a new temporary cluster by using *New Machine Cluster Generation Rule*.

1	2

Third, machine pair {2, 3} is located. Since this machine pair has a connection to the temporary cluster, machine 3 is adjacently located to machine 2 by using *Adoption Rule*.

1	2
	3

Fourth, machine pair {6,7} is located to facility layout. This machine pair has a connection to the first cluster. So, machine 7 is adjacently located to machine 6 by using *Adoption Rule*.

6	
7	8

Fifth, machine pair {1,4} is located to facility layout. Machine pair {1, 4} has a connection to the temporary cluster. So, machine 4 is adjacently located to machine 1 by using *Adoption Rule*.

1	2
4	3

Sixth, machine pair {2,4} is already located to facility layout. Therefore, there is no need to execute any rule. Seventh, similarly, machine pair {3,4} is already located. Eighth, machine pair {5,6} is located to facility layout. This machine pair has a connection to the existing cluster. So, machine 6 is adjacently located to machine 5 by using *Adoption Rule*.

6	5
7	8

Ninth, machine pair {6, 4} is already located to facility layout. But, machine 4 and machine 6 are located to different clusters. Therefore, machine pair {6,4} has a connection to these two machine clusters. We combine these two different clusters into one cluster by using *Merging Rule.*

1	2
4	3
6	5
7	8

Tenth, machine pair {9, 10} has no connection to the existing cluster. Then, we assign this machine pair to a new temporary cluster by using *New Machine Cluster Generation Rule*.

9	10

Eleventh, all of the machines are located in the workspace and there are more than one cluster. These clusters are combined into one cluster to obtain the final facility layout. In combining these clusters, the cluster which is obtained in step nine is determined as the main cluster. Herein, we apply *Final Assembly Rule.* The final layout is given in the following.

1	2
4	3
6	5
7	8
9	10

3.2 MINWAL(W)-Based Approaches

In this section, we proposed two new approaches based on mining normalized weighted association rules, MINWAL(W), for facility layout problems. In MINWAL (W), the weight of a machineset is normalized by the number of machine in that machineset. The proposed approaches are presented in the following.

3.2.1 First Approach

The first approach for MINWAL(W) is exactly the same as MINWAL(O), except the definition of k-support bound.

- k-support bound of *Y*: the minimum count for a large k-machinesets containing Y is given by

$$B(Y,k) = ((wminsup * T* k) / W(Y,k)) \tag{3}$$

We called this "k-support bound of *Y*" for MINWAL(W). Using the value of third equation we determine an upper bound for *B(Y,k)* since it should take an integer value.

3.2.2 Second Approach

Basic definitions related to the second MINWAL(W)-based approach are presented in the following.

- Support(A, B): Number of transitions (part routes) containing both A and B (machineset A and B). When we count the number of transitions for a machineset, we only take adjacent machineset into account.

The support (A, B) is given by;

$$\sup port(\mathrm{A},\mathrm{B}) = \frac{\text{number of transactions containing both A and B adjacently}}{\text{total number of transactions}} \tag{4}$$

- Normalized weighted support *(NWS):* The normalized weighted support value is calculated as follows.

Given a set of machines (I_1, I_2,..., I_n), we assign a weight, w_j (where $0<w_j<1$) for each machine. The NWS value of a A→B is given by

$$\left(\frac{\sum i_{j \in (A \cup B)} w_j}{k} \right) x \sup port(A,B) \tag{5}$$

- Large machine(s)/machineset(s): If the normalized weighted support value of a machine(s)/machineset(s) is equal or higher than the weighted minimum support value, we call that machine(s)/machineset(s) large machine(s)/ machineset(s).

- Prune: A machineset(A,B) will be pruned if the normalized weighted support value (A,B) is not equal or higher than weighted minimum support threshold value.

- Low-order superset: For a machineset K={K_1, K_2,…, K_n}, let the smallest weight of the machines be w_i. A machineset $T = K \cup L$, where the machines in L having weights less than w_i is called a low-order superset of K.

- Join: We apply low-order superset definition to join some machines/ machinesets. For example, assume that $w_1 < w_2 < w_3 < w_4 < w_5 < w_6 < w_7$ are weights of machines {1,2,3,4,5,6,7}, and machine pair {3,7} is a 2-level large machineset. The join step will locate {1,3,7} and {2,3,7} machineset only for

3-level. Those joined machineset will be put in C_k. Machinesets {4,3,7}, {5,3,7} and {6,3,7} can not be a large itemset.

Second MINWAL(W)-based approach can also be categorized into two stages. Stage 1, presented in Figure 3.4, involves data manipulation based on MINWAL(W). Stage 2 is the same as stage 2 of MINWAL (O)-based approach, and deals with the location of the machines.

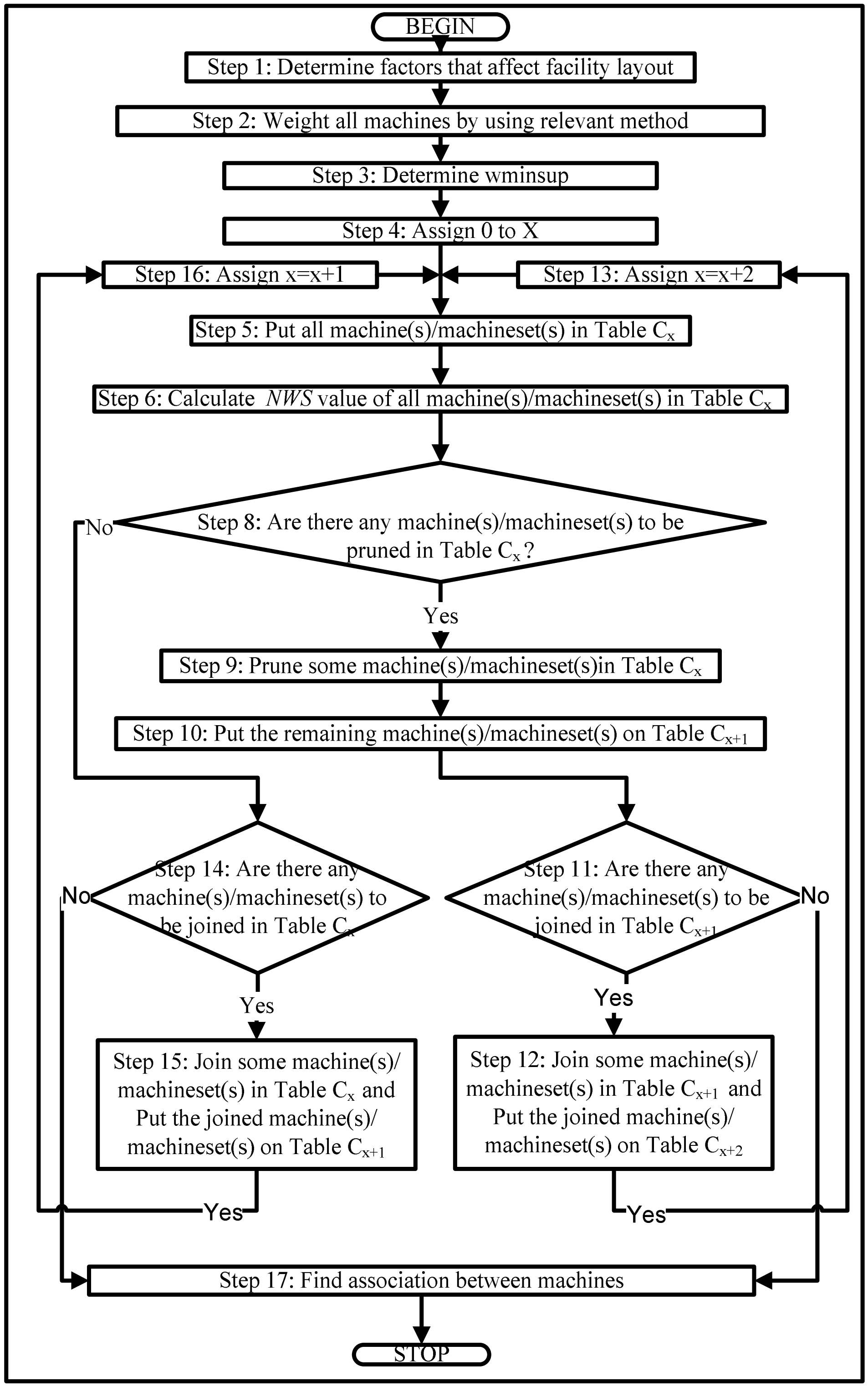


Figure 3.1 The algorithm of the proposed MINWAL(W)-based approach to find association between machines

3.3 WARM-Based Approach

In this section, we introduce some basic descriptions for better understanding of the proposed WARM-based approach.

- Weighted Product: Every product is weighted by using machine weights. To assign a weight to product A, we sum the weight of all machines which are on the route of the product. Weighted product is the total weight of all machines in a single transaction.

- Weighted Machine Pair: In order to weight machine pair {a,b}, we sum the weight of products which contain machine pair{a,b}. We only take into account adjacent machine pair in transitions.

WARM-based approach can also be categorized into two stages. Stage 1 involves data manipulation based on WARM approach, while stage 2 deals with the construction of machine layout. The steps of these stages are illustrated in Figures 3.5 and 3.6, respectively.

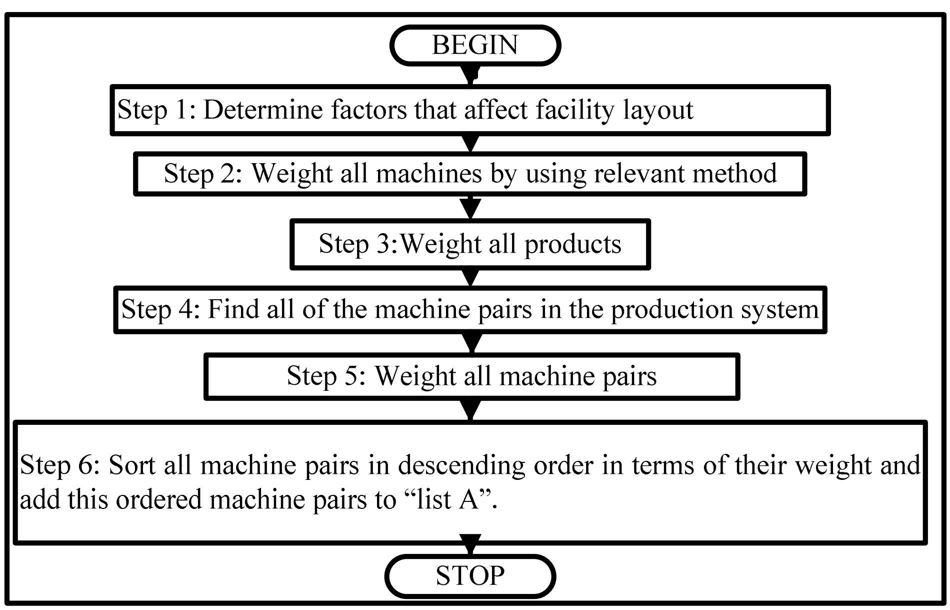


Figure 3.5 The algorithm of the first stage of the proposed WARM-based approach

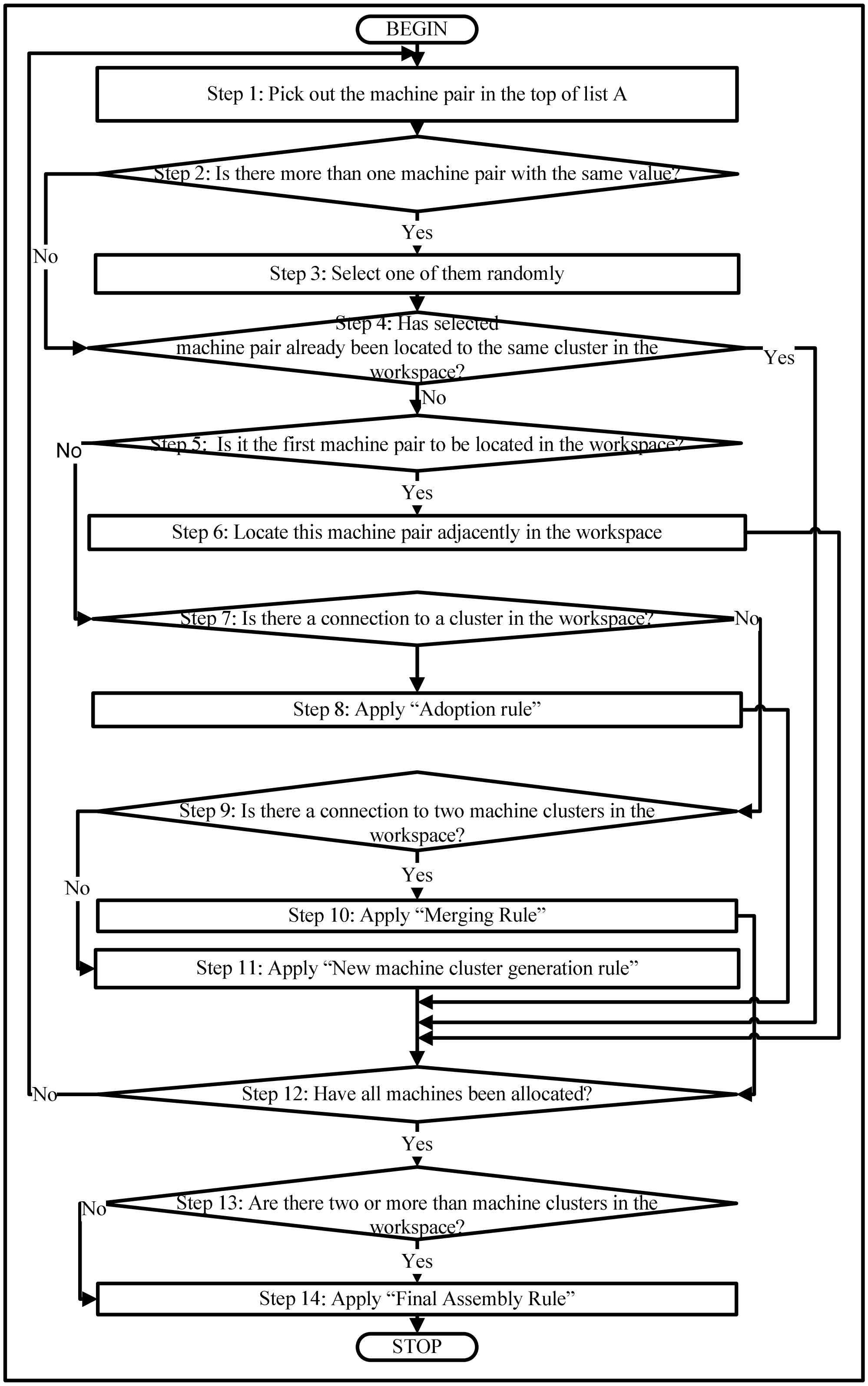


Figure 3.6 Location algorithm of the proposed WARM-based approach

3.4 BWARM-Based Approach

Basic definitions related to the proposed BWARM-based approach are presented in the following.

- Machine Pair Transaction Weight *(MTW): MTW* is the aggregated weight of all machines in the machine pair that is adjacent in a single transition.

- Weighted Support *(WS(X)):* WS is the aggregated sum of machine pair transaction weight *(MTW)* of all transactions in which machine pair is adjacent, divided by the total number of transactions.

A small example is given herein to show how to calculate *MTW* and *WS(X)*. The product routes are given in Table 3.3, while machines and associated weights are given in Table 3.4.

Table 3.3 Product Route

Product	Route		
P1	a	b	c
P2	a	b	
P3	b	c	

Table 3.4 Machines and associated weights

Machine	Weight
a	0.1
b	0.2
c	0.7

MTW(a,b) = (The weight of machine *a*)*(The weight of machine *b*) = 0.1*0.2 = 0.02.

WS(a,b)=((Total number of product (transition) in which machine pair is adjacent) * *MTW(a,b))* / total number of transactions)

WS(a,b)=((2*0.02)/3)= 0.0133

BWARM-based approach can be categorized into two stages. The steps of the first stage are presented in Figure 3.7. Stage 2 is the same as stage 2 of WARM approach.

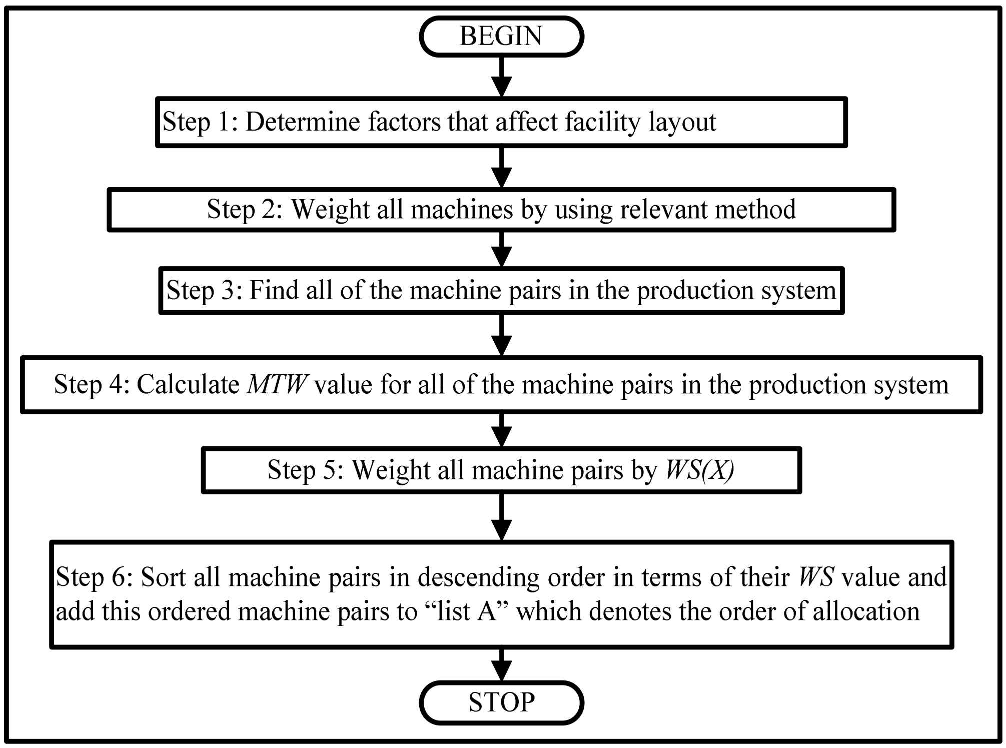


Figure 3.7 The algorithm of the first stage of the proposed BWARM-based approach

3.5 Conclusion

In this chapter, five proposed approaches based on weighted association rules, namely MINWAL (O), MINWAL (W), BWARM and WARM, are introduced. Their flow algorithms and basic descriptions are established. The goal of those approaches is to obtain sufficient facility layout with respect to some user defined criteria and to establish a methodology which may consider qualities and quantities criteria which are addable to model when arranging facility layout. The next chapter, the feasibility of the proposed approaches when applied to different size problems is detailed with different case studies.

CHAPTER FOUR
APPLICATION

To confirm the viability of the proposed approaches, two case studies are presented in this chapter. The approaches are compared in terms of general performance criteria for the facility layout problems using simulation. The first case study deals with the facility layout problem with 4 products and 9 machines, while the second case considers a problem with 15 products and 30 machines.

4.1 Case Study-I (4 Products, 9 Machines)

As stated above, the first case study deals with the facility layout problem with 4 products and 9 machines. A hypothetical production system is designed for this implementation. Four products, namely Product1, Product2, Product3 and Product4, and nine machines, denoted by 1, 2, 3,…, 9, are considered in this system. The assumptions relating to the production system are as follows:

- Each machine can perform one operation at most at a time,
- Each part may visit each machine only once,
- The processing times are known and stochastic in nature,
- There is no setup times for machines,
- All of the machines have the same dimensions,
- The process sequence of each product is known,
- Material transport distance between machines is calculated as a vertical linear and based on a centroid to centroid procedure.

The products' routes are given in Table 4.1. While demand patterns of each product (frequency of the arrivals) are reported in Table 4.2, the workspace is illustrated in Figure 4.1. The stochastic processing times of the products are presented in Table 4.3

Table 4.1 The products' routes

Products	Processing sequence					
Product1	1	2	3	4	8	
Product2	1	2	4	6	7	8
Product3	2	3	5	7	8	
Product4	1	4	5	6	7	8	9

Table 4.2 Demand patterns of the products

Product	Frequency of the arrivals (min)
Product1	Exponential (10.26)
Product2	Exponential (6.60)
Product3	Exponential (7.70)
Product4	Exponential (8.22)

Machine x	Machine x	Machine x
Machine x	Machine x	Machine x
Machine x	Machine x	Machine x

Figure 4.1 The workspace

Table 4.3 Processing times of the products

Product	Machine	Distribution (min)
Product1	1	N (4;1.2)
Product1	2	N (3;0.8)
Product1	3	N (2;0.5)
Product1	4	N (6;2.2)
Product1	8	N (4;1.2)
Product2	1	N (2.5;1.1)
Product2	2	N (3.3;0.9)
Product2	4	N (5.5;2.1)
Product2	6	N (6;2.4)
Product2	7	N (3;0.3)
Product2	8	N (1.8;0.2)
Product3	2	N (4;1.5)
Product3	3	N (3.3;1.3)
Product3	5	N (3;0.8)
Product3	7	N (2.2;0.7)
Product3	8	N (4;1.5)
Product4	1	N (2;0.5)
Product4	4	N (5;1.5)
Product4	5	N (4.8;2.5)
Product4	6	N (5;1.9)
Product4	7	N (4.6;1.6)
Product4	8	N (7;2.2)
Product4	9	N (3;1.2)

4.1.1 Implementation of the MINWAL(O)-Based Approach

Implementation stages of the MINWAL(O)-based approach consist of two main stages as presented in Figures 3.1, 3.2 and 3.3. Implementation of these stages are explained in detail in the following sections.

4.1.1.1 Implementation of the First Stage

All steps in Figure 3.1 are followed for responding to which machine to be assigned with which order to facility layout.

Step 1. *Determine factors that affect facility layout*

As stated previously, three key location factors that are most pertinent to facility layout problems are selected in the case studies handled in this thesis. These factors are, demand, part-handling factor and efficiency of material handling equipment. The priority weights of these location factors are computed by using pairwise comparison.

Step 2: *Weight all machines by using relevant method*

In this thesis, products are weighted using AHP with respect to three key location factors mentioned above. Then, machines are weighted by using weighted products. In other words, there are two steps to follow in weighting the machines. First step includes the calculation of product weight by using AHP. A weight of machine is calculated by summing of the products' weights.

The AHP is based on the innate human ability to make sound judgments about small problems (Satty, 1994). A pairwise comparison judgment matrix is the fundamental process of AHP. It uses a scale which has numerical expression from 1 to 9 to construct pairwise comparison judgment matrix. Experts who are relevant related decision area use this scale to express how much one element dominates another with respect to a common criterion during construction of pairwise comparison judgment matrix. Consistency ratio is calculated for each constructed pairwise comparison judgment matrix. This ratio has to be less than 0.1 to be acceptable. Pairwise comparison scale for AHP preferences is given in Table 4.5. The following definitions are given to understand calculation of consistency ratio (CR) clearly.

A: Pairwise comparison judgment matrix
W: The weights of the criteria
CI: Consistency Index
RI: Random Consistency Index
CR: Consistency Ratio

Random Consistency Index (RI) is given in Table 4.4.

$$A = \begin{pmatrix} A_1 & B_1 & . & . & C_1 \\ A_2 & B_2 & . & . & C_2 \\ . & . & . & . & . \\ . & . & . & . & . \\ A_n & B_n & . & . & C_n \end{pmatrix} \qquad W = \begin{pmatrix} W_1 \\ W_2 \\ . \\ . \\ W_n \end{pmatrix} \qquad AXW = \begin{pmatrix} X_1 \\ X_2 \\ . \\ . \\ X_n \end{pmatrix} \tag{6}$$

$$\Lambda_{\max} = \left(\sum_{i=1}^{n} X_i \right) \tag{7}$$

$$CI = \frac{\Lambda_{\max} - n}{n-1} \tag{8}$$

Table 4.4. Random Consistency Index (RI)

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

$$CR = \frac{CI}{RI} \tag{9}$$

Table 4.5 Pairwise comparison scale for AHP preferences (Satty, 1994)

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one activity over another
5	Strong importance	Experience and judgment strongly favor one activity over another
7	Very strong or demonstrated importance	An activity is favored very strongly over another, its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	For compromise between the above values	Sometimes one needs to interpolate a compromise judgment numerically because there is no good word to describe it
Reciprocals of above	If activity *i* has one of the above nonzero numbers assign to it when compared with activity *j* then *j* has the reciprocal value when compared with *i*	A comparison mandated by choosing the smaller element as the unit to estimate the larger one as a multiple of that unit.
Rationales	Ratios arising from the scale	If consistency were to be forced by obtaining n numerical values to span the matrix
1.1-1.9	For tied activities	When elements are close and nearly in distinguishable; moderate is 1,3 and extreme is 1,9

The products in the production system considered are weighted with respect to the location factors by using pairwise comparison matrices. Consistency ratio is calculated for each pairwise comparison matrices. The first factor, demand, is a quantitative factor so, there is no need to calculate its consistency and construct pairwise comparison matrix. Weights of the products with respect to their demands are presented in Table 4.6. Similarly, we constructed the pairwise comparison matrices for the other factors, part-handling factor and efficiency of equipment used for material handling. Results are reported in Tables 4.7 and 4.8, respectively. Additionally, pairwise comparison matrix for the factors and calculation of the products' weights are given in Tables 4.9 and 4.10, respectively. Weight of a machine is calculated by summing the weight(s) of the product(s) that this machine is used in their route. The calculated machine weights are presented in Table 4.11.

Table 4.6 Weights of the products with respect to their demands

product	quantity	normalized weight
Product_1	180	0.195
Product_2	280	0.303
Product_3	240	0.259
Product_4	225	0.243
TOTAL	925	1

Table 4.7 Pairwise comparison matrix with respect to part-handling factor

	Product_1	Product_2	Product_3	Product_4	Weight
Product_1	1	3	6	3	0.505
Product_2	1/3	1	4	5	0.310
Product_3	1/6	1/4	1	1	0.083
Product_4	1/3	1/5	1	1	0.103
consistency ratio 0.09					

Table 4.8 Pairwise comparison matrix with respect to efficiency of equipment used for material handling

	Product_1	Product_2	Product_3	Product_4	Weight
Product_1	1	2	2	3	0.406
Product_2	1/2	1	2	3	0.288
Product_3	1/2	1/2	1	3	0.208
Product_4	1/3	1/3	1/3	1	0.098
consistency ratio 0.05					

Table 4.9 Pairwise comparison matrix for the factors

		factors			weight
		1	2	3	
Factors	1	1	3	5	0.619
	2	1/3	1	4	0.284
	3	1/5	1/4	1	0.096
consistency ratio 0.07					

Table 4.10 Calculation of the products' weights

weight of the first factor	weight of the second factor	weight of the third factor		weight of the factors		weight of the products
0.195	0.505	0.406	x	0.619	=	Product_1= 0.303
0.303	0.310	0.288		0.284		Product_2 =0.303
0.259	0.083	0.208		0.096		Product_3 =0.204
0.243	0.103	0.098				Product_4= 0.190

Table 4.11 The machine weights

machine	weight	normalized weight
1	0.796	0.140
2	0.810	0.142
3	0.507	0.089
4	0.795	0.140
5	0.393	0.069
6	0.507	0.089
7	0.696	0.122
8	0.999	0.176
9	0.189	0.033
Total	5.692	1.000

For instance, let us explain the calculation of the weight of machine 1. As can be seen above, machine 1 is on the route of Product_1, Product_2 and Product_4. Therefore, the weights of these products are summed to calculate the weight of machine 1, which is 0.796 (0.303+0.303+0.190). Then this weight is normalized to obtain the final weight of machine 1.

Step 3: *Determine wminsup*

Association rules are considered meaningful if they satisfy weighted minimum support (wminsup) threshold value. In this study, we determine three different wminsup threshold values to compare the effect of wminsup threshold value on facility layout. These wminsup values are 0.2, 0.3 and 0.4.

Step 4: *Determine size (k)*

Size (k) equals the largest number of machines that a product route includes. In our production system, the largest number of machine, 7, exist in the route of Product_4.

Step 5: *Assign 0 to " x"*

Step 6: *Put all machine(s)/machineset(s) in Table C_x*

We construct Table C_0 because x=0. Table C_0 is given in the following.

Table C_0

Machines	1	2	3	4	5	6	7	8	9

Step 7: *Calculate W(Y,k) for all machine(s)/machineset(s) in Table C_x*

In calculating the *W(Y,k)*, the following formula is used. The *W(Y,k)* values are presented in Table 4.12.

$$W(Y,k) = \sum_{i_j \in Y} w_j + \sum_{i_j \in Y}^{k-q} w_{r_j} \tag{10}$$

Table 4.12 W(Y,k) values

$W(Y,k)$	$\sum_{i_j \in Y} w_j$	$\sum_{i_j \in Y}^{k-q} w_{r_j}$						$W(Y,k)=\sum_{i_j \in Y} w_j+\sum_{i_j \in Y}^{k-q} w_{r_j}$
$W(1,7)$	0.140	0.176	0.142	0.140	0.122	0.089	0.089	0.898
$W(2,7)$	0.142	0.176	0.140	0.140	0.122	0.089	0.089	0.898
$W(3,7)$	0.089	0.176	0.142	0.140	0.140	0.122	0.089	0.898
$W(4,7)$	0.140	0.176	0.142	0.140	0.122	0.089	0.089	0.898
$W(5,7)$	0.069	0.176	0.142	0.140	0.140	0.122	0.089	0.878
$W(6,7)$	0.089	0.176	0.142	0.140	0.140	0.122	0.089	0.898
$W(7,7)$	0.122	0.176	0.142	0.140	0.140	0.089	0.089	0.898
$W(8,7)$	0.176	0.142	0.140	0.140	0.122	0.089	0.089	0.898
$W(9,7)$	0.033	0.142	0.140	0.140	0.122	0.089	0.089	0.755

Step 8: *Calculate B(Y,k) for all machine(s)/machineset(s) in Table C_x*

In calculating the *B(Y,k)*, the following formula is used. Herein, Wminsup value is taken as 0,2, while the value of T is 4 since the number of products is 4. The resulting *B(Y,k)* values are reported in Table 4.13.

$$B(Y,k)=\left(\frac{w\min\sup * T}{W(Y,k)}\right) \tag{11}$$

Table 4.13 B(Y,k) values

B(Y,k)	wminsup	T	wminsup * T	W(Y,k)	B(Y,k) = (wminsup * T) / W(Y,k)
B(1,7)	0.2	4	0.8	0.898	0.891~ 1
B(2,7)	0.2	4	0.8	0.898	0.891~ 1
B(3,7)	0.2	4	0.8	0.898	0.891~ 1
B(4,7)	0.2	4	0.8	0.898	0.891~ 1
B(5,7)	0.2	4	0.8	0.878	0.911~ 1
B(6,7)	0.2	4	0.8	0.898	0.891~ 1
B(7,7)	0.2	4	0.8	0.898	0.891~ 1
B(8,7)	0.2	4	0.8	0.898	0.891~ 1
B(9,7)	0.2	4	0.8	0.755	1.059~ 2

Step 9: Calculate SC(X) value for all machines/machineset(s) in Table C_x and add SC value to C_x

The counts of the machines {1,2,3,4,5,6,7,8,9} are {3,3,2,3,2,2,3,4,1}, respectively. Then, Table C_0 takes the following form.

Table C_0

Machines	1	2	3	4	5	6	7	8	9
SC	3	3	2	3	2	2	3	4	1

Step 10: *Are there any machine(s)/machineset(s) to be pruned* in Table C_x? (Rule (i))

The counts of all machines, except machine 9, are greater than the *B(Y,k)* values. SC value of machine 9 is smaller than its $B(9,7)$ value, which is 2. Therefore, we go to step 11.

Step 11: *Prune some machine(s)/machineset(s) in Table C_x*

We prune machine 9 in Table C_0

Step 12: *Put the remaining machine(s)/machineset(s) on Table C_{x+1}*

We construct Table C_1 because x=1. Table C_1 is given in the following

Table C_1

Machines	1	2	3	4	5	6	7	8

Step 13: *Are there any machine(s)/machineset(s) to be joined in Table C_{x+1}?*

There are machines to be joined in Table C_1. So, we go to step 14.

Step 14: *Join some machine(s)/machineset(s) in Table C_{x+1} and put the joined machine(s)/machineset(s) on Table C_{x+2}.*

Total 28 machinesets (with 2-level) are obtained by joining. These machinesets are presented in Table C_2.

Table C_2. 2-level Machinesets

	1	2	3	4	5	6	7	8	9	10
X	{1,2}	{1,3}	{1,4}	{1,5}	{1,6}	{1,7}	{1,8}	{2,3}	{2,4}	{2,5}

	11	12	13	14	15	16	17	18	19	20
X	{2,6}	{2,7}	{2,8}	{3,4}	{3,5}	{3,6}	{3,7}	{3,8}	{4,5}	{4,6}

	21	22	23	24	25	26	27	28
X	{4,7}	{4,8}	{5,6}	{5,7}	{5,8}	{6,7}	{6,8}	{7,8}

Step 15: *Are there any machine(s)/machineset(s) to be pruned* in Table C_{x+2}? (Rule (ii))

A subset of all machinesets in C_2 exists in C_1. Therefore, there are not any machineset(s) to be pruned in Table C_2. Now, we go to Step 17.

Step 17: *Are there any machine(s)/machineset(s) to calculate its/their W(Y,k) in Table* C_{x+2} ?

There is no pruned machinesets in Table C_2. Therefore, the answer of this question is yes. We go to Step 18.

Step 18: *Assign* $x=x+2$.

In this step, we assign $x= x+2$. Therefore, we will use the last table, C_2.

Step 6: *Put all machine(s)/machineset(s) in Table* C_x

We put all machinesets in Table C_x in advance. Table C_2 have already been constructed in step14.

Step 7: *Calculate W(Y,k) for all machine(s)/machineset(s) in Table C_x*

Resulting 2-level *W(Y,k)* values are given in Table 4.14.

Table 4.14 2-level *W(Y,k)* values

W(Y,k)	$\sum_{i_j \in Y} w_j$		$\sum_{i_j \in Y}^{k-q} w_{r_j}$					$W(Y,k) = \sum_{i_j \in Y} w_j + \sum_{i_j \in Y}^{k-q} w_{r_j}$
$W((1,2),7)$	0.140	0.142	0.176	0.140	0.122	0.089	0.089	0.898
$W((1,3),7)$	0.140	0.089	0.176	0.142	0.140	0.122	0.089	0.898
$W((1,4),7)$	0.140	0.140	0.176	0.142	0.122	0.089	0.089	0.898
$W((1,5),7)$	0.140	0.069	0.176	0.142	0.140	0.122	0.089	0.878
$W((1,6),7)$	0.140	0.089	0.176	0.142	0.140	0.122	0.089	0.898
$W((1,7),7)$	0.140	0.122	0.176	0.142	0.140	0.089	0.089	0.898
$W((1,8),7)$	0.140	0.176	0.142	0.140	0.122	0.089	0.089	0.898
$W((2,3),7)$	0.142	0.089	0.176	0.140	0.140	0.122	0.089	0.898
$W((2,4),7)$	0.142	0.140	0.176	0.140	0.122	0.089	0.089	0.898
$W((2,5),7)$	0.142	0.069	0.176	0.140	0.140	0.122	0.089	0.878
$W((2,6),7)$	0.142	0.089	0.176	0.140	0.140	0.122	0.089	0.898
$W((2,7),7)$	0.142	0.122	0.176	0.140	0.140	0.089	0.089	0.898
$W((2,8),7)$	0.142	0.176	0.140	0.140	0.122	0.089	0.089	0.898
$W((3,4),7)$	0.089	0.140	0.176	0.142	0.140	0.122	0.089	0.898
$W((3,5),7)$	0.089	0.069	0.176	0.142	0.140	0.140	0.122	0.878
$W((3,6),7)$	0.089	0.089	0.176	0.142	0.140	0.140	0.122	0.898
$W((3,7),7)$	0.089	0.122	0.176	0.142	0.140	0.140	0.089	0.898
$W((3,8),7)$	0.089	0.176	0.142	0.140	0.140	0.122	0.089	0.898
$W((4,5),7)$	0.140	0.069	0.176	0.142	0.140	0.122	0.089	0.878
$W((4,6),7)$	0.140	0.089	0.176	0.142	0.140	0.122	0.089	0.898
$W((4,7),7)$	0.140	0.122	0.176	0.142	0.140	0.089	0.089	0.898
$W((4,8),7)$	0.140	0.176	0.142	0.140	0.122	0.089	0.089	0.898
$W((5,6),7)$	0.069	0.089	0.176	0.142	0.140	0.140	0.122	0.878
$W((5,7),7)$	0.069	0.122	0.176	0.142	0.140	0.140	0.089	0.878
$W((5,8),7)$	0.069	0.176	0.142	0.140	0.140	0.122	0.089	0.878
$W((6,7),7)$	0.089	0.122	0.176	0.142	0.140	0.140	0.089	0.898
$W((6,8),7)$	0.089	0.176	0.142	0.140	0.140	0.122	0.089	0.898
$W((7,8),7)$	0.122	0.176	0.142	0.140	0.140	0.089	0.089	0.898

Step 8: *Calculate B(Y,k) for all machine(s)/machineset(s) in Table C_x*

Resulting 2-level *B(Y,k)* values are given in Table 4.15.

Table 4.15 2-level *B(Y,k)* values

B(Y,k)	*wminsup*	*T*	Wminsup* T	*W(Y,k)*	*B(Y,k) = (wminsup* T) / W(Y,k)*
B ((1,2), 7)	0.2	4	0.8	0.898	0.891~ 1
B ((1,3), 7)	0.2	4	0.8	0.898	0.891~ 1
B ((1,4), 7)	0.2	4	0.8	0.898	0.891~ 1
B ((1,5), 7)	0.2	4	0.8	0.878	0.911~ 1
B ((1,6), 7)	0.2	4	0.8	0.898	0.891~ 1
B ((1,7), 7)	0.2	4	0.8	0.898	0.891~ 1
B ((1,8), 7)	0.2	4	0.8	0.898	0.891~ 1
B ((2,3), 7)	0.2	4	0.8	0.898	0.891~ 1
B ((2,4), 7)	0.2	4	0.8	0.898	0.891~ 1
B ((2,5), 7)	0.2	4	0.8	0.878	0.911~ 1
B ((2,6), 7)	0.2	4	0.8	0.898	0.891~ 1
B ((2,7), 7)	0.2	4	0.8	0.898	0.891~ 1
B ((2,8), 7)	0.2	4	0.8	0.898	0.891~ 1
B ((3,4), 7)	0.2	4	0.8	0.898	0.891~ 1
B ((3,5), 7)	0.2	4	0.8	0.878	0.911~ 1
B ((3,6), 7)	0.2	4	0.8	0.898	0.891~ 1
B ((3,7), 7)	0.2	4	0.8	0.898	0.891~ 1
B ((3,8), 7)	0.2	4	0.8	0.898	0.891~ 1
B ((4,5), 7)	0.2	4	0.8	0.878	0.911~ 1
B ((4,6), 7)	0.2	4	0.8	0.898	0.891~ 1
B ((4,7), 7)	0.2	4	0.8	0.898	0.891~ 1
B ((4,8), 7)	0.2	4	0.8	0.898	0.891~ 1
B ((5,6), 7)	0.2	4	0.8	0.878	0.911~ 1
B ((5,7), 7)	0.2	4	0.8	0.878	0.911~ 1
B ((5,8), 7)	0.2	4	0.8	0.878	0.911~ 1
B ((6,7), 7)	0.2	4	0.8	0.898	0.891~ 1
B ((6,8), 7)	0.2	4	0.8	0.898	0.891~ 1
B ((7,8), 7)	0.2	4	0.8	0.898	0.891~ 1

Step 9: *Calculate SC(X) value for all machines/machineset(s) in Table C_x and add SC value to C_x*

The counts of the machinesets are added to Table C_2. The new form of Table C_2 is given in the following.

Table C_2

	1	2	3	4	5	6	7	8	9	10
X	{1,2}	{1,3}	{1,4}	{1,5}	{1,6}	{1,7}	{1,8}	{2,3}	{2,4}	{2,5}
support	2	0	1	0	0	0	0	2	1	0

	11	12	13	14	15	16	17	18	19	20
X	{2,6}	{2,7}	{2,8}	{3,4}	{3,5}	{3,6}	{3,7}	{3,8}	{4,5}	{4,6}
support	0	0	0	1	1	0	0	0	1	1

	21	22	23	24	25	26	27	28
X	{4,7}	{4,8}	{5,6}	{5,7}	{5,8}	{6,7}	{6,8}	{7,8}
support	0	1	1	1	0	2	0	3

Step 10: *Are there any machine(s)/machineset(s) to be pruned in Table C_x?* (Rule (i))

Machineset(s) which its/their SC value is less than the *B(Y,k)* value (1) are pruned. The answer of this question is yes, then, we go to Step 11.

Step 11: *Prune some machine(s)/machineset(s) in Table C_x*

15 machinesets are pruned in this step, These are; {1,3}, {1,5}, {1,6}, {1,7}, {1,8}, {2,5}, {2,6}, {2,7}, {2,8}, {3,6}, {3,7}, {3,8}, {4,7}, {5,8}, {6,8}.

Step 12: Put the remaining machine(s)/machineset(s) on Table C_{x+1}

We put the remaining machinesets on Table C_3, given in the following.

Table C_3

machineset	{1,2}	{1,4}	{2,3}	{2,4}	{3,4}	{3,5}	{4,5}
SC	2	1	2	1	1	1	1

machineset	{4,6}	{4,8}	{5,6}	{5,7}	{6,7}	{7,8}
SC	1	1	1	1	2	3

Step 13*: Are there any machine(s)/machineset(s) to be joined in Table C_{x+1}*

The answer is; yes, there are machines to be joined. So we go to step 14.

Step 14: *Join some machine(s)/machineset(s) in Table C_{x+1} and put the joined machine(s)/machineset(s) on Table C_{x+2}.*

Total 4 machinesets (3-level) are obtained by joining. The machinesets are {1,2,4}, {2,3,4}, {3,4,5}, {4,5,6}, and {6,7,5}. These are given in Table C_4

Table C_4.

Machineset	{1,2,4}	{2,3,4}	{3,4,5}	{4,5,6}	{6,7,5}.

Step 15*: Are there any machineset(s) to be pruned in Table C_{x+2}? (*Rule (ii))

All subsets of machinesets in C_4 exist in C_3. Therefore, the answer is no. Then, we go to Step 17.

Step 17: *Are there any machine(s)/machineset(s) to calculate its/their W(Y,k) in Table C_{x+2}?*

The answer is yes. Therefore, we go to Step 18.

Step 18: *Assign x=x+2.*

In this step, we assign x= x+2. Therefore, we will use the last table which is C_4. We go to Step 6.

Step 6: *Put all machine(s)/machineset(s) in Table C_x*

We put all machinesets in Table C_x in advance. Table C_4 has already been constructed in the latest step 14.

Step 7: *Calculate W(Y,k) for all machine(s)/machineset(s) in Table C_x*

Resulting 3-level W(Y,k) values are given in Table 4.16.

Table 4.16 3-level *W(Y,k)* values

W(Y,k)	$\sum_{i_j \in Y} w_j$			$\sum_{i_j \in Y}^{k-q} w_{r_j}$				$W(Y,k)= \sum_{i_j \in Y} w_j + \sum_{i_j \in Y}^{k-q} w_{r_j}$
W((1,2,4), 7)	0.140	0.142	0.140	0.176	0.122	0.089	0.089	0.898
W((2,3,4), 7)	0.142	0.089	0.140	0.176	0.140	0.122	0.089	0.898
W((3,4,5), 7)	0.089	0.140	0.069	0.176	0.142	0.140	0.122	0.878
W((4,5,6), 7)	0.140	0.069	0.089	0.176	0.142	0.140	0.122	0.878
W((6,7,5), 7)	0.089	0.122	0.069	0.176	0.142	0.140	0.140	0.878

Step 8: *Calculate B(Y,k) for all machine(s)/machineset(s) in Table C_x.*

3-level *B(Y,k)* values are given in Table 4.17.

Table 4.17 Results of B(Y,k) values for 3-level

B(Y,k)	*wminsup*	*T*	*Wminsup*T*	*W(Y,k)*	*B(Y,k) = (wminsup*T) / W(Y,k)*
B((1,2,4), 7)	0.2	4	0.8	0.898	0.891~ 1
B((2,3,4), 7)	0.2	4	0.8	0.898	0.891~ 1
B((3,4,5), 7)	0.2	4	0.8	0.878	0.911~ 1
B((4,5,6), 7)	0.2	4	0.8	0.878	0.911~ 1
B((6,7,5), 7)	0.2	4	0.8	0.878	0.911~ 1

Step 9: *Calculate SC(X) value of all machines/machineset(s) in Table C_x and add SC value to C_x*

The counts of the machinesets are added to Table C_4. The new form of Table C_4 is given in the following.

Table C_4

Machineset	{1,2,4}	{2,3,4}	{3,4,5}	{4,5,6}	{6,7,5}
SC	1	1	0	1	1

Step 10: *Are there any machine(s)/machineset(s) to be pruned in Table C_x?*

The counts of the machineset {3,4,5} is less than the result of *B(Y,k)* value (1). Therefore, this machineset should be pruned.

Step 11: *Prune some machine(s)/machineset(s) in Table C_x.*

We prune machineset {3,4,5}.

Step 12: *Put the remaining machine(s)/machineset(s) on Table C_{x+1}*

We put the remaining machinesets on Table C_5 that is given in the following.

Table C_5 (The remaining machinesets in Table C_4)

Machineset	{1,2,4}	{2,3,4}	{4,5,6}	{6,7,5}

Step 13: *Are there any machine(s)/machineset(s) to be joined in Table C_{x+1}.*

There are machines to be joined. So we go to step 14.

Step 14: *Join some machine(s)/machineset(s) in Table C_{x+1} and put the joined machine(s)/machineset(s) on Table C_{x+2}*

Total 8 machinesets (4-level) are obtained by joining. These machinesets are {1,2,4,3}, {1,2,4,5},{1,2,4,6},{1,2,4,7},{2,3,4,5},{2,3,4,6},{2,3,4,7}, and {4,5,6,7}. These are given in Table C_6.

Table C_6

Machineset	{1,2,4,3}	{1,2,4,5}	{1,2,4,6}	{1,2,4,7}	{2,3,4,5}	{2,3,4,6}	{2,3,4,7}	{4,5,6,7}

Step 15*: Are there any machineset(s) to be pruned in Table C_{x+2}?* (Rule(ii))

All subsets of machinesets in C_6 does not exist in C_5. Therefore, the answer is yes. We go to Step 16.

Step 16*: Prune some machine(s)/machineset(s) in Table C_{x+2}*

All machinesets in Table C_6 is pruned because of the fact that all subsets of machinesets in C_6 does not exist in C_5.

Step 17*: Are there any machine(s)/machineset(s) to calculate its/their W(Y,k) in Table C_{x+2}?*

The answer is no. Therefore, we go to Step 25.

Step 25: *Find associations between machines.*

The final association between machines are obtained as fallows; {1,2,4}, {2,3,4}, {4,5,6}, and {6,7,5}.

4.1.1.2 Implementation of the Second Stage

The steps presented in Figure 3.3 are followed at the second stage. As stated previously, the second stage responds to which machine to be located with which area in facility layout. Implementation of these steps for case study-I is explained in the following.

Step 1: *Are there more than 2-level-associations among machines?*

Since, we find 3-level-association at the end of stage 1, the answer of the question is yes. The 3-level-associations are; {1,2,4}, {2,3,4}, {4,5,6}, and {6,7,5}. Therefore, we go to step 2.

Step 2: *If there are more than one k-level-association, select one k-level-association rule randomly (k-level equals to the level obtained at the end of stage 1)*

In this case study, *k*-level equals to 3. Then, we choose {1,2,4} randomly as a *k*-level association.

Step 3: *Separate the levels up to 2-level for the selected k-level-association (If we have k-level at the end of stage 1, we divide it into C(k,2) piece of the 2-level subsets(machine pairs)).*

Machineset {1,2,4} is divided into three 2-level subsets (machine pairs). These are; {1, 2}, {1, 4} and {2, 4}.

Step 4: *Calculate the support counts of all 2-level subsets*

The support counts of the machine pairs {1,2}, {1,4} and {2,4} are {2,1,1}.

Step 5: *Pick out the machine pair with the highest support count (If there are more than one machine pair with the same highest support count, select one of them randomly).*

The machine pair {1, 2} has the highest support count value, which is 2.

Step 6: *Has the selected machine pair already been located to the same cluster in the workspace?*

The answer of this question is no. Then, we go to step 7.

Step 7: *Is it the first machine pair to be located in the workspace?*

The machine pair {1,2} is the first machine pair to be located in the workspace. Therefore, the answer of this question is yes. Then we go to step 8.

Step 8: *Locate this machine pair adjacently in the workspace*

We locate this machine pair in the workspace. This forms the first cluster. Then, we go to step 14.

1	2

Step 14: *Are there any 2-level subsets (machine pair) of the selected k-level association that were not located in the workspace?*

The answer of this question is yes. Since, we select machineset {1, 2, 4} and its subsets, namely {1,4} and {2,4} which were not located in the workspace. Then, we go to step 5.

Step 5: *Pick out the machine pair with the highest support count (If there are more than one machine pair with the same highest support count, select one of them randomly).*

Selected machineset is {1,2,4}. The subsets of this machineset are; {1,2}, {1,4} and {2,4}. Machineset {1, 2} is located in the workspace in advance. The remaining machinesets are {1,4} and {2,4}. The support count of these machinesets is {1,1}. Herein, we select machineset {1,4} randomly since the remaining machinests have the same support counts, which is 1.

Step 6: *Has the selected machine pair already been located to the same cluster in the workspace?*

The answer is no. Then, we go to step 7.

Step 7: *Is it the first machine pair to be located in the workspace?*

The answer of this question is no. Therefore, we go to step 9.

Step 9: *Is there a connection to a cluster in the workspace?*

Since, the last selected machine pair in step 5, {1,4}, has a connection to the first cluster, the answer of this question is yes.

Step 10: *Apply "Adoption rule"*

Machine pair {1,4} is located to facility layout. Since this machine pair has a connection to the first cluster, machine 4 is adjacently located to machine 1 by using *Adoption Rule.* Then we go to step 14.

1	2
4	

Step 14: *Are there any 2-level-subsets (machine pair) of the selected k-level association that were not located in the workspace?*

Since we selected machineset {1,2,4} and its subsets, namely {2,4}, were not located in the workspace, the answer of this question is yes. Then, we go to step 5.

Step 5: *Pick out the machine pair with the highest support count (If there are more than one machine pair with the highest support count, select one of them randomly)*

We select machine pair {2,4} and go to step 6.

Step 6: *Has the selected machine pair already been located to the same cluster in the workspace?*

Since, machine pair {2,4} is already located in the workspace, the answer of this question is yes. Therefore, we go to step 14.

Step 14: *Are there any 2-level-subsets (machine pair) of the selected k-level association that were not located in the workspace?*

The answer of this question is no. Therefore, we go to step 15.

Step 15: *Have all machines been allocated?*

Only three machines, namely machine 1, machine 2 and machine 4, are allocated in the workspace. Therefore, the answer of this question is no. Then, we go to step 2.

Step 2: *If there are more than one k-level-association, select one k-level association rule randomly (k-level equals to the level obtained at the end of stage 1)*

We choose {2,3,4} randomly as the k-level association in the remaining k-level-associations, which are {2,3,4}, {4,5,6} and {6,7,5}.

Step 3: *Separate the levels up to 2-level for the selected k-level-association (If we have k-level at the end of stage 1, we divide it into C(k,2) piece of the 2-level subsets(machine pairs)).*

Machineset {2,3,4} is divided into three 2-level subsets (machine pairs). These are; {2,3}, {2,4} and {3,4}.

Step 4: *Calculate support counts of all 2-level subsets*

The support counts of machine pairs {2,3}, {2,4} and {3,4} are {2,1,1}.

Step 5: *Pick out the machine pair with the highest support count (If there are more than one machine pair with the same highest support count, select one of them randomly).*

The machine pair {2,3} has the highest support count value, which is 2.

Step 6: *Has the selected machine pair already been located to the same cluster in the workspace?*

The answer of this question is no. Then, we go to step 7.

Step 7: *Is it the first machine pair to be located in the workspace?*

The answer of this question is no. Then, we go to step 9.

Step 9: *Is there a connection to a cluster in the workspace?*

Since the last selected machine pair in step 5, {2,3}, has a connection to the first cluster, the answer of this question is yes.

Step 10: *Apply "Adoption rule"*

Machine pair {2,3} is located. Since this machine pair has a connection to the first cluster, machine 3 is adjacently located to machine 1 by using *Adoption Rule.* We go to step 14.

1	2
4	3

Step 14: *Are there any 2-level-subsets (machine pair) of the selected k-level association that were not located in the workspace?*

The answer of this question is no. Because, we selected machineset {2,3,4} and its subsets, namely {2,4} and {3,4}, which were located in the workspace. Therefore, we go to step 15.

Step 15: *Have all machines been allocated?*

Only four machines, machines 1-4, are allocated in the workspace. Therefore, the answer of this question is no. Then, we go to step 2.

Step 2: *If there are more than one k-level-association, select one k-level-association randomly (k-level equals to the level obtained at the end of stage 1).*

We choose {6,7,5} randomly as the *k*-level-association in the remaining *k*-level-associations, which are {4,5,6} and {6,7,5}.

Step 3: *Separate the levels up to 2-level for the selected k-level-association (If we have k-level at the end of stage 1, we divide it into C(k,2) piece of the 2-level subsets(machine pairs)).*

Machineset {6,7,5} is divided into three 2-level subsets (machine pairs). These are; {6,7}, {6,5} and {7,5}.

Step 4: *Calculate support counts of all 2-level subsets*

The support counts of the machine pairs {6,7}, {6,5}, {7,5} are {2,1,1} respectively.

Step 5: Pick out the machine pair with the highest support count (If there are more than one machine pair with the same highest support count, select one of them randomly).

The machine pair {6,7} has the highest support count value, which is 2.

Step 6: *Has the selected machine pair already been located to the same cluster in the workspace?*

The answer of this question is no. Then, we go to step 7.

Step 7: *Is it the first machine pair to be located in the workspace?*

The answer of this question is no. Therefore, we go to step 9.

Step 9: *Is there a connection to a cluster in the workspace?*

The answer of this question is no. Then, we go to step 11.

Step 11: *Is there a connection to two machine clusters in the workspace?*

The answer of this question is no. Then, we go to step 13.

Step 13: *Apply "New machine cluster generation rule"*.

Machine pair {6,7} has no connection to any existing cluster. So, we assign this machine pair to a new temporary cluster by using *New Machine Cluster Generation Rule*. Then, we go to step 14.

6	7

Step 14: *Are there any 2-level-subsets (machine pair) of the selected k-level association that were not located in the workspace?*

The answer of this question is yes. Because, we selected machineset {6,7,5} and its subsets, namely {6,5} and {7,5} which were not located in the workspace. Then we go to step 5.

Step 5: *Pick out the machine pair with the highest support count (If there are more than one machine pair with the same highest support count, select one of them randomly).*

We select machine pair {7,5}, and go to step 6.

Step 6: *Has the selected machine pair already been located to the same cluster in the workspace?*

The answer of this question is no. Therefore, we go to step 7.

Step 7: *Is it the first machine pair to be located in the workspace?*

The answer of this question is no. Therefore, we go to step 9.

Step 9: *Is there a connection to a cluster in the workspace?*

The answer of this question is yes. Therefore, we go to step 10.

Step 10: *Apply "Adoption rule"*

The last selected machine pair in step 5 is {7,5}. Since this machine pair has a connection to the existing cluster, the answer of this question is yes. So, machine 5 is adjacently located to machine 7 by using *Adoption Rule*.

6	7
	5

Step 14: *Are there any 2-level-subsets (machine pair) of the selected k-level association that were not located in the workspace?*

The answer of this question is no. Therefore, we go to step 15.

Step 15: *Have all machines been allocated?*

All associated machines are allocated to the workspace. Therefore, the answer of this question is yes. Then, we go to step 16.

Step 16: *Are there two or more machine clusters in the workspace?*

The answer of this question is yes. We go to step 17.

Step 17: *Apply "Final Assembly Rule"*

All associated machines are located in the workspace, and there are two clusters. While, the first cluster includes machines 1 to 4, second cluster includes machines 5 to 7. These clusters are combined into one cluster to obtain the final facility layout. In combining the clusters, the cluster which has the biggest number of machine is selected as the main cluster. Herein, first cluster is selected as the main cluster, while second cluster called temporary cluster. Starting from the first machine pair which is located to create the temporary clusters, we locate machine pairs to the appropriate locations in the main cluster. All machines in the temporary clusters will be located to the main cluster until the temporary cluster is depleted. Finally, we obtain single cluster which is called "final facility layout" after applying the final assembly rule. Finally facility layout is given in the following.

1	2	
4	3	
6	7	5

4.1.1.3 Construction of machineset(s) with no association

We execute the algorithm presented in Figure 3.2 to locate the remaining machines, machines 8 and 9, to facility layout. Implementation of these steps are explained in the following.

Step 1: *Find all machine pairs among which there is no association.*

Machines {8,9} have no association.

Step 2: *Calculate SC value for all of these machine pairs in the production system*

SC value of machine pair {8,9} is 1.

Step 3: *Sort all machine pairs in descending order in terms of their SC values, and add this ordered machine pairs to "List A" which denotes the order of allocation to facility layout*

There is only one machine pair. Therefore, there is no need to sort.

List A	{8,9}

We use the algorithm presented in Figure 3.3 to locate the ordered machine pairs in List A. The final facility layout is illustrated in Figure 4.2.

1	2	9
4	3	8
6	7	5

Figure 4.2 Final facility layout (wminsup = 0.2)

In this implementation, we use three different threshold values for wminsup, 0.2, 0.3 and 0.4. The facility layouts corresponding to threshold values of 0.3 and 0.4 are the same. As the threshold value increases, the number of association between machines decreases. The final facility layout corresponding to threshold values of 0.3 and 0.4 is illustrated in Figure 4.3.

4	5	9
6	7	8
1	2	3

Figure 4.3 Final facility layout (wminsup=0.3 and 0.4)

4.1.2 Implementation of the MINWAL(W)-Based Approaches

4.1.2.1 First Approach

The first approach is exactly the same as MINWAL (O)-based approach, except that the definition of *k*-support bound is changed. In our implementation, we use the threshold value of 0.04 in the mining for the normalized weights case. To generate a reasonable number of associated machines, this threshold value is determined in a different way compared to MINWAL (O)-based approach. Herein, we do not explain all of the steps in the two stages of the approach that creates the final facility layout. But, only some important steps are explained. Table 4.18 presents the results of the MINWAL(W)-based approach.

Table 4.18 *B(Y,k)* values for the MINWAL (W)-based approach

B(Y,k)	*wminsup*	*T*	*Wminsup* T*	*W(Y,k)*	*B(Y,k) = (wminsup* T* k) / W(Y,k)*
B(1,7)	0.04	4	0.16	0.898	1.248~2
B(2,7)	0.04	4	0.16	0.898	1.248~2
B(3,7)	0.04	4	0.16	0.898	1.248~2
B(4,7)	0.04	4	0.16	0.898	1.248~2
B(5,7)	0.04	4	0.16	0.878	1.276~2
B(6,7)	0.04	4	0.16	0.898	1.248~2
B(7,7)	0.04	4	0.16	0.898	1.248~2
B(8,7)	0.04	4	0.16	0.898	1.248~2
B(9,7)	0.04	4	0.16	0.755	1.483~2

The counts of the machines are given in the following.

Machines	1	2	3	4	5	6	7	8	9
SC	3	3	2	3	2	2	3	4	1

The counts of all machines, except machine 9, are greater than or equal to corresponding *B(Y,k)* values. Therefore, machine 9 that is pruned (Rule(i)). The machine pairs obtained by joining the machines are presented in the following. The results of *B(Y,k)* values for 2-level-association of MINWAL(W)-based approach are given in Table 4.19.

	1	2	3	4	5	6	7	8	9	10
X	{1,2}	{1,3}	{1,4}	{1,5}	{1,6}	{1,7}	{1,8}	{2,3}	{2,4}	{2,5}
Support	2	0	1	0	0	0	0	2	1	0

	11	12	13	14	15	16	17	18	19	20
X	{2,6}	{2,7}	{2,8}	{3,4}	{3,5}	{3,6}	{3,7}	{3,8}	{4,5}	{4,6}
Support	0	0	0	1	1	0	0	0	1	1

	21	22	23	24	25	26	27	28
X	{4,7}	{4,8}	{5,6}	{5,7}	{5,8}	{6,7}	{6,8}	{7,8}
Support	0	1	1	1	0	2	0	3

The counts of machine pairs {7,8}, {6,7}, {2,3} and {1,2} are equal to or greater than the corresponding *B(Y,k)* values. We use the same method for the remaining passes, until "Final Assembly Rule" is applied. The final facility layout obtained by using MINWAL(W)-based approach with wminsup=0,04 is presented in Figure 4.4.

4	5	9
6	7	8
1	2	3

Figure 4.4 Final facility layout (wminsup=0,04)

Table 4.19 B(Y,k) values for 2-level MINWAL(W)-based approach.

B(Y,k)	*wminsup*	*T*	*Wminsup* T*	*W(Y,k)*	*B(Y,k) = (wminsup* T* k) / W(Y,k)*
B ((1,2), 7)	0.04	4	0.16	0.898	1.248~2
B ((1,3), 7)	0.04	4	0.16	0.898	1.248~2
B ((1,4), 7)	0.04	4	0.16	0.898	1.248~2
B ((1,5), 7)	0.04	4	0.16	0.878	1.276~2
B ((1,6), 7)	0.04	4	0.16	0.898	1.248~2
B ((1,7), 7)	0.04	4	0.16	0.898	1.248~2
B ((1,8), 7)	0.04	4	0.16	0.898	1.248~2
B ((2,3), 7)	0.04	4	0.16	0.898	1.248~2
B ((2,4), 7)	0.04	4	0.16	0.898	1.248~2
B ((2,5), 7)	0.04	4	0.16	0.878	1.276~2
B ((2,6), 7)	0.04	4	0.16	0.898	1.248~2
B ((2,7), 7)	0.04	4	0.16	0.898	1.248~2
B ((2,8), 7)	0.04	4	0.16	0.898	1.248~2
B ((3,4), 7)	0.04	4	0.16	0.898	1.248~2
B ((3,5), 7)	0.04	4	0.16	0.878	1.276~2
B ((3,6), 7)	0.04	4	0.16	0.898	1.248~2
B ((3,7), 7)	0.04	4	0.16	0.898	1.248~2
B ((3,8), 7)	0.04	4	0.16	0.898	1.248~2
B ((4,5), 7)	0.04	4	0.16	0.878	1.276~2
B ((4,6), 7)	0.04	4	0.16	0.898	1.248~2
B ((4,7), 7)	0.04	4	0.16	0.898	1.248~2
B ((4,8), 7)	0.04	4	0.16	0.898	1.248~2
B ((5,6), 7)	0.04	4	0.16	0.878	1.276~2
B ((5,7), 7)	0.04	4	0.16	0.878	1.276~2
B ((5,8), 7)	0.04	4	0.16	0.878	1.276~2
B ((6,7), 7)	0.04	4	0.16	0.898	1.248~2
B ((6,8), 7)	0.04	4	0.16	0.898	1.248~2
B ((7,8), 7)	0.04	4	0.16	0.898	1.248~2

In this implementation, we use three different threshold values for wminsup, 0.04, 0.07 and 0.08. The facility layouts corresponding to threshold values of 0.07 and 0.08 are the same. The final facility layout corresponding to threshold values of 0.3 and 0.4 is illustrated in Figure 4.5.

1	2	9
4	3	5
6	7	8

Figure 4.5 Final facility layout (wminsup=0.07and 0.08)

4.1.2.2 Second Approach

The SCs of the machines {1,2,3,4,5,6,7,8,9} will be {3,3,2,3,2,2,3,4,1}. Considering these counts, for example, the weighted support of machine 3 will be (0,089*2)/4 = 0.0445. The normalized weighted support (NWS) of the machines are obtained as {0.10500, 0.10650, 0.04450, 0.10500, 0.03450, 0.04450, 0.09150, 0.17600, 0.00825}. In this implementation, we determine wminsup value as 0.04. Since its NWS value is less than 0.04, machine 5 is pruned. Hence, C_1={{1},{2},{3},{ 4},{6},{7},{8},{9}}. After the implementation of "join step", the algorithm will generate the following potential machinesets.

Machineset	{1,2}	{1,4}	{2,3}	{2,4}	{3,4}	{3,5}	{4,5}
SC	2	1	2	1	1	1	1

Machineset	{4,6}	{4,8}	{5,6}	{5,7}	{6,7}	{7,8}	{9,8}
SC	1	1	1	1	2	3	1

For instance, during the "prune step", the estimated weighted support value of machineset {1,2} is obtained as follows.

$$\frac{(0{,}14+0{,}142)}{2}\,x\,\frac{2}{4}=0{,}0705$$

The other weighted support values are obtained in the same way. The results are reported in Table 4.20.

Herein, machinesets {1,4}, {2,4}, {3,4}, {3,5}, {4,5}, {4,6},{4 ,8}, {5,6}, {5,7} and {8,9} will be pruned. Hence, C_2= {{1,2},{2,3},{6,7},{7,8}}.

The weighted support values for 3-level machinesets are presented Table 4.21.

Table 4.20 Weighted support values for 2-level machinesets

Machineset	{1,2}	{1,4}	{2,3}	{2,4}	{3,4}	{3,5}	{4,5}
SC	2	1	2	1	1	1	1
Weighted support	0.0705	0.035	0.05775	0.03525	0.02863	0.01975	0.02613

Machineset	{4,6}	{4,8}	{5,6}	{5,7}	{6,7}	{7,8}	{8,9}
SC	1	1	1	1	2	3	1
Weighted support	0.02863	0.0395	0.01975	0.02388	0.05275	0.11175	0.02613

There are no 3-level machinesets that its weighted support value is higher than wminsup value (0.04). Therefore, all of the 3-level machinesets are pruned. In this implementation, we found the same machinesets associations as our first MINWAL (W)-based approach. Therefore, the final facility layout is the same as the one obtained by that approach presented in Figure 4.4.

As in the first MINWAL(W)-based approach, we use three different threshold values for wminsup, 0.04, 0.07 and 0.08 in the second MINWAL(W)-based approach. But, we do not find any association between machines for the threshold values of 0.07 and 0.08. As conclusion, we can not obtain any facility layouts corresponding to these threshold values.

Table 4.21 Weighted support values for 3-level machinesets

	A	B	C	D	D/4
machineset	total weight of machineset	A/3	support count	B*C	weighted support
{1,2,4}	0.4217	0.1406	1	0.1406	0.0351
{1,2,7}	0.4043	0.1348	0	0.0000	0.0000
{1,2,6}	0.3711	0.1237	0	0.0000	0.0000
{1,2,3}	0.3711	0.1237	1	0.1237	0.0309
{1,2,5}	0.3511	0.1170	0	0.0000	0.0000
{1,2,9}	0.3152	0.1051	0	0.0000	0.0000
{2,3,5}	0.3005	0.1002	1	0.1002	0.0250
{2,3,9}	0.2646	0.0882	0	0.0000	0.0000
{6,7,3}	0.3005	0.1002	0	0.0000	0.0000
{6,7,5}	0.2805	0.0935	1	0.0935	0.0234
{6,7,9}	0.2446	0.0815	0	0.0000	0.0000
{7,8,6}	0.3870	0.1290	1	0.1290	0.0322
{7,8,3}	0.3869	0.1290	0	0.0000	0.0000
{7,8,5}	0.3669	0.1223	1	0.1223	0.0306
{7,8,9}	0.3311	0.1104	1	0.1104	0.0276

4.1.3 WARM Based Approach

Details of the implementation of the proposed WARM-based approach are presented in the following.

Step 1: *Determine the factors that affect facility layout.*

This step is the same as step 1 at stage 1 of the proposed MINWAL(O)-based approach.

Step 2: *Weight all machines by using a relevant method.*

This step is also the same as step 2 at stage 1 of the proposed MINWAL(O)-based approach.

Step 3: *Weight all products.*

We weight all of the products, and report the results in Table 4.22. For instance, we calculate the weight of Product_1 in the following.

The route of Product_1 is "Machine 1- Machine 2- Machine 3- Machine 4- Machine 8". The weights of these machines are 0.140, 0.142, 0.089, 0.140 and 0.176, respectively. The sum of the weight of these machines is 0.687.

Table 4.22 The weight of products

products	weight	normalized weight
Product_1	0.687	0.240
Product_2	0.809	0.283
Product_3	0.598	0.209
Product_4	0.769	0.269
Total	2.863	1.000

Step 4: *Find all of the machine pairs in the production system.*

The machine pairs obtained are presented in Table 4.23.

Table 4.23 Machine pairs.

	1	2	3	4	5	6	7
{a-b}	{7-8}	{6-7}	{1-2}	{2-3}	{2-4}	{4-6}	{1-4}

	8	9	10	11	12	13	14
{a-b}	{4-5}	{5-6}	{8-9}	{3-4}	{4-8}	{3-5}	{5-7}

Step 5: *Weight all machine pairs*

The weighted machine pairs are reported in Table 4.24. For instance, we calculate the weight of machine pair {7-8} in the following. Machine pair {7-8} is on the route of Products 2-3 and 4. So, the weights of these products are summed, and the resulting weight is 0.761 (0.283+0.209+0.269).

Table 4.24 Weighted machine pairs

	1	2	3	4	5	6	7
{a-b}	{7-8}	{6-7}	{1-2}	{2-3}	{2-4}	{4-6}	{1-4}
Weight	0.761	0.551	0.523	0.449	0.283	0.283	0.269

	8	9	10	11	12	13	14
{a-b}	{4-5}	{5-6}	{8-9}	{3-4}	{4-8}	{3-5}	{5-7}
Weight	0.269	0.269	0.269	0.240	0.240	0.209	0.209

Step 6: *Sort all machine pairs in descending order in terms of their weights and add this ordered machine pairs to "list A".*

List A is presented in Table 4.25.

Table 4.25 List A

machine pair{a,b}	weight
{7-8}	0.760
{6-7}	0.551
{1-2}	0.523
{2-3}	0.449
{2-4}	0.283
{4-6}	0.283
{1-4}	0.269
{4-5}	0.269
{5-6}	0.269
{8-9}	0.269
{3-4}	0.240
{4-8}	0.240
{3-5}	0.209
{5-7}	0.209

Using the proposed WARM-based approach, the order of allocation to facility layout (stage 1) is completed. Then, we proceed to the second stage responding to which machine to be located to which area in facility layout. Herein, we use the location algorithm presented in Figure 3.5. Details of the implementation steps for this location algorithm are presented in the following.

Step 1*: Pick out the machine pair at the top of list A*

Machine pair {7,8} is at the top of list A in our example, thus, we select it.

Step 2: *Is there more than one machine pair with the same value?*

The answer of this question is no. So, we go to step 4.

Step 4: *Has the selected machine pair already been located to the same cluster in the workspace?*

The answer of this question is no. So, we go to step 5.

Step5: *Is it the first machine pair to be located in the workspace?*

The answer of this question is yes. Therefore, we go to Step 6.

Step 6*: Locate this machine pair adjacently in the workspace.*

We locate this machine pair adjacently as follows and go to step 12.

7	8

Step 12: *Have all machines been allocated?*

The answer of this question is no. Therefore, we go to Step 1.

Step 1*: Pick out the machine pair at the top of list A.*

Machine pair {6,7} is at the top of list A in our example, thus, we select it.

Step 2: *Is there more than one machine pair with the same value?*

The answer of this question is no. So, we go to step 4.

Step 4: *Has the selected machine pair already been located to the same cluster in the workspace?*

The answer of this question is no. So, we go to step 5.

Step 5: *Is it the first machine pair to be located in the workspace?*

The answer of this question is no. Therefore, we go to Step 7.

Step 7: *Is there a connection to a cluster in the workspace?*

The answer of this question is yes. Therefore, we go to Step 8.

Step 8: *Apply "Adoption rule"*

We apply the rule, and create the following cluster. Then, we go to step 12.

7	8
6	

Step 12: *Have all machines been allocated?*

The answer of this question is no. Therefore, we go to Step 1.

Step 1*: Pick out the machine pair at the top of list A.*

Machine pair {1,2} is at the top of list A in our example, thus, we select it.

Step 2: *Is there more than one machine pair with the same value?*

The answer of this question is no. So, we go to step 4.

Step 4: *Has the selected machine pair already been located to the same cluster in the workspace?*

The answer of this question is no. So, we go to step 5.

Step 5: *Is it the first machine pair to be located in the workspace?*

The answer of this question is no. Therefore, we go to Step 7.

Step 7: *Is there a connection to a cluster in the workspace?*

The answer of this question is no. Therefore, we go to Step 9

Step 9: *Is there a connection to two machine clusters in the workspace?*

The answer of this question is no. Therefore, we go to Step 11

Step 11: *Apply "New machine cluster generation rule"*

We apply the rule and create the following cluster.

1	2

Step 12: *Have all machines been allocated?*

The answer of this question is no. Therefore, we go to Step 1.

Step 1*: Pick out the machine pair in the top of list A*

Herein machine pair {2,3} is selected.

Step 2: *Is there more than one machine pair with the same value?*

The answer of this question is no. So, we go to step 4.

Step 4: *Has the selected machine pair already been located to the same cluster in the workspace?*

The answer of this question is no. So, we go to step 5.

Step 5: *Is it the first machine pair to be located in the workspace?*

The answer of this question is no. Therefore, we go to Step 7.

Step 7: *Is there a connection to a cluster in the workspace?*

The answer of this question is yes. Therefore, we go to Step 8

Step 8*: Apply "Adoption rule"*

We apply the rule and obtained the following cluster. Then, we go to step 12.

1	2	3

Step 12: *Have all machines been allocated?*

The answer of this question is no. Therefore, we go to Step 1.

Step 1: *Pick out the machine pair in the top of list A*

Herein, machine pairs {2,4}and {4,6} are selected.

Step 2: *Is there more than one machine pair with the same value?*

The answer of this question is yes. So, we go to step 3

Step 3: *Select one of them randomly.*

We selected machine pair {2,4} randomly. Then, we go to step 4.

Step 4: *Has the selected machine pair already been located to the same cluster in the workspace?*

The answer of this question is no. So, we go to step 5.

Step 5: *Is it the first machine pair to be located in the workspace?*

The answer of this question is no. Therefore, we go to Step 7.

Step 7: *Is there a connection to a cluster in the workspace?*

The answer of this question is yes. Therefore, we go to Step 8.

Step 8: *Apply "Adoption rule"*

We apply the rule and create the following cluster. Then, we go to step 12.

	4	
1	2	3

Step 12: *Have all machines been allocated?*

The answer of this question is no. Therefore, we go to Step 1.

Step 1*: Pick out the machine pair in the top of list A*

Herein, machine pair {4,6} is selected.

Step 2: *Is there more than one machine pair with the same value?*

The answer of this question is no. So, we go to step 4.

Step 4*: Has the selected machine pair already been located to the same cluster in the workspace?*

The answer of this question is no. So, we go to step 5.

Step 5: *Is it the first machine pair to be located in the workspace?*

The answer of this question is no. Therefore, we go to Step 7.

Step 7: *Is there a connection to a cluster in the workspace?*

The answer of this question is no. Therefore, we go to Step 9

Step 9: Is there a connection to two machine clusters in the workspace?

The answer of this question is yes. Therefore, we go to Step 9.

Step 10: *Apply "Merging Rule"*

We apply the rule and obtain the following cluster. Then, we go to step 12.

7	8	
6	4	
1	2	3

Step 12: *Have all machines been allocated?*

The answer of this question is no. Therefore, we go to Step 1.

Step 1*: Pick out the machine pair in the top of list A*

Machine pairs {1,4}, {4,5}, {5,6} and {8,9} are selected.

Step 2: *Is there more than one machine pair with the same value?*

The answer of this question is yes. So, we go to step 3

Step 3: *Select one of them randomly.*

We select machine pair {4, 5} randomly. Then, we go to step 4

Step 4: *Has the selected machine pair already been located to the same cluster in the workspace?*

The answer of this question is no. So, we go to step 5.

Step 5: *Is it the first machine pair to be located in the workspace?*

The answer of this question is no. Therefore, we go to Step 7.

Step 7: *Is there a connection to a cluster in the workspace?*

The answer of this question is yes. Therefore, we go to Step 8.

Step 8: *Apply "Adoption rule"*

We apply the rule and create the following cluster. Then, we go to step 12.

7	8	
6	4	5
1	2	3

Step 12: *Have all machines been allocated?*

The answer of this question is no. Therefore, we go to Step 1.

Step 1*: Pick out the machine pair in the top of list A*

Machine pairs {1,4}, {5,6} and {8,9} are selected.

Step 2: *Is there more than one machine pair with the same value?*

The answer of this question is yes. So, we go to step 3

Step 3: *Select one of them randomly.*

Since the other machine pairs have already been located to facility layout, we select machine pair {8,9}. Then, we go to step 4.

Step 4: *Has the selected machine pair already been located to the same cluster in the workspace?*

The answer of this question is no. So, we go to step 5.

Step 5: *Is it the first machine pair to be located in the workspace?*

The answer of this question is no. Therefore, we go to Step 7.

Step 7: *Is there a connection to a cluster in the workspace?*

The answer of this question is yes. Therefore, we go to Step 8.

Step 8: *Apply "Adoption rule"*

We apply the rule and obtain the final facility layout given in Figure 4.6. Then, we go to step 12.

7	8	9
6	4	5
1	2	3

Figure 4.6 The final facility layout for the proposed WARM-based approach

Step 12: *Have all machines been allocated?*

The answer of this question is yes. Therefore, we stop.

4.1.4 BWARM-Based Approach

Details of the implementation steps of the proposed BWARM-based approach are presented in the following. Like the proposed WARM-based approach, the first two steps are the same as step 1 and step 2 at stage 1 of the proposed MINWAL(O)-based approach. Therefore, we begin with step 3 to explain the details of the proposed BWARM-based approach.

Step 3: *Find all of the machine pairs in the production system.*

Total number of machine pairs in the production system is 14. The machine pairs have already been presented in Table 4.23.

Step 4: *Calculate MTW value for all of the machine pairs in the production system.*

The calculated *MTW* values are given in Table 4.26.

Step 5: *Weight all machine pairs by WS(X).*

The calculated *WS(X)* values are also given in Table 4.26.

Step 6: *Sort all machine pairs in descending order in terms of their WS value and add this ordered machine pairs to "list A" which denotes the order of allocation.*

Sorted machine pairs are given in Table 4.26.

Table 4.26 MTW, WS and sorted machine pairs.

machine pair (a,b)	MTW (a,b)
{1-2}	0.0199
{1-4}	0.0195
{2-3}	0.0127
{2-4}	0.0199
{3-4}	0.0124
{3-5}	0.0062
{4-6}	0.0124
{4-5}	0.0096
{5-7}	0.0084
{5-6}	0.0062
{6-7}	0.0109
{7-8}	0.0215
{8-4}	0.0245
{8-9}	0.0058

machine pair (a,b)	WS (a,b)
{1-2}	0.0099
{1-4}	0.0049
{2-3}	0.0063
{2-4}	0.0050
{3-4}	0.0031
{3-5}	0.0015
{4-6}	0.0031
{4-5}	0.0024
{5-7}	0.0021
{5-6}	0.0015
{6-7}	0.0054
{7-8}	0.0161
{8-4}	0.0061
{8-9}	0.0015

sorted machine pair (a,b)	WS (a,b)
{7-8}	0.0161
{1-2}	0.0099
{2-3}	0.0063
{8-4}	0.0061
{6-7}	0.0054
{2-4}	0.0050
{1-4}	0.0049
{4-6}	0.0031
{3-4}	0.0031
{4-5}	0.0024
{5-7}	0.0021
{5-6}	0.0015
{3-5}	0.0015
{8-9}	0.0015

BWARM-based approach can also be categorized into two stages. Stage 1 involves data manipulation based on BWARM, and Stage 2 deals with construction of machine layout. Stage 2 is the same as stage 2 of the proposed WARM-based approach. The final facility layout obtained by the proposed BWARM-based approach is illustrated in Figure 4.7.

7	8	1
6	4	2
9	5	3

Figure 4.7 Final facility layout for the proposed BWARM-based approach

4.1.5 Simulation Outputs

Law and McComas (1997) indicate that one of the most common application areas of simulation is manufacturing. For instance, (Shambu and Suresh, 2000), (Abduelmula and Wagner, 2004), (Morris and Tersine, 1990), (Jeong and Kim, 1998), (Mosier, Elvers and Kelly, 1984)), (Assad, Kramer, and Kaku, 2003), (Felix, Chan, and Abhary, 1996), (Zolfaghari and Roa, 2006), (Kamrani, Hubbard, Parsaep, and Leew, 1998) use simulation to analyze manufacturing systems.

We employ simulation in this study to evaluate and compare the final layouts obtained by the proposed approaches. The comparison is made in terms of general performance criteria for the facility layout problems. The simulation models are run by PROMODEL simulation software. The models are run for 480 hours, representing a three-month period (8 hours a day, 5 days per week, 4 weeks per month, 3 moth= 8 hours*5 days*4 weeks*3months=480 hours).

The warm up period is determined as 30 hours. The behaviors of the products are observed while determining this period. The amounts of product produced per unit time corresponding to different layouts for case study-I are illustrated in the figures presented in Appendix A. The model is run 100 times for each facility layout. In determining the number of replication, the warm up period is taken into consideration. Moving averages of the amount of production for each replication corresponding to different layouts for case study-I are illustrated in figures presented in Appendix B. The common random numbers are used as variance reduction technique.

Facility layouts obtained by the proposed approaches are illustrated in Figure 4.8. First layout corresponds to the proposed MINWAL(O)-based approach (wminsup=0.2), while second layout corresponds to the layout by the same approach with different wminsup values (0.3 and 0.4) and MINWAL(W) based first and second approaches (wminsup=0.04). Additionally, the third, fourth and fifth layouts correspond to the proposed MINWAL(W)-based first approach with different wminsup values (0.07 and 0.08), WARM-based and BWARM-based approaches, respectively. Five performance measures are employed in our experiments. These measures are; machine utilization, total amount of products produced, cycle time, transfer time and waiting time in queue.

Layout 1

1	2	9
4	3	8
6	7	5

Layout 2

4	5	9
6	7	8
1	2	3

Layout 3

1	2	9
4	3	5
6	7	8

Layout 4

7	8	9
6	4	5
1	2	3

Layout 5

7	8	1
6	4	2
9	5	3

Figure 4.8 Facility layouts obtained by the proposed approaches

As reported in Table 4.27, the highest machine utilization is obtained by the MINWAL(O)-based approach with wminsup value of 0.2.

Table 4.27 Machine utilizations (%)

Product	Layout 1	Layout 2	Layout 3	Layout 4	Layout 5
M 1	87.110	88.239	86.025	86.103	86.242
M 4	68.430	51.669	66.989	59.163	59.456
M 7	41.250	27.904	33.046	28.669	29.338
M 2	82.753	81.847	80.617	79.909	79.873
M 5	18.355	17.235	27.054	31.538	31.794
M 8	24.356	23.601	26.830	27.107	28.185
M 3	53.131	45.260	48.170	43.358	43.324
M 6	33.937	27.097	31.343	40.796	41.192
M 9	4.667	4.292	5.063	5.014	5.000

The total amounts of products produced are given in Table 4.28. The highest total amount of product is obtained by the facility layout corresponding to the WARM-based approach, while the lowest total amount of product is obtained by facility layout given by the MINWAL(O)-based approach (wminsup=0.3 and 0,4) and MINWAL(W) based first and second approaches (wminsup=0.04). The reason for this is that the lowest machine utilizations are obtained by these approaches.

Table 4.28 The total amount of products produced

Product	Layout 1	Layout 2	Layout 3	Layout 4	Layout 5
Product 1	364.12	332.23	393.18	391.91	385.34
Product 2	562.91	515.24	610.08	602.48	597.48
Product 3	355.33	416.41	409.14	443.23	445.28
Product 4	447.59	411.46	486.41	481.91	479.32
Total	1729.95	1675.34	1898.81	1919.53	1907.42

Tables 4.29, 4.30 and 4.31 reports the cycle time, respectively transfer time and waiting time in queue of each product corresponding to each layout type. Cycle time of a product is calculated by summing the transfer time, waiting time in queue and operation time on the machines. Table 4.29 shows cycle time of each product and average time between any consecutive products corresponding to each layout type. The lowest average time between consequences any products is obtained by the proposed WARM-based approach. Therefore, the highest total amount of products produced is obtained by this approach. As concluded from Table 4.30, the lowest transfer time for Product1 is obtained by the MINWAL(O)-based approach with wminsup values of 0.2, WARM and BWARM -based approaches, while the lowest transfer time for Product2 is obtained by WARM and BWARM-based approaches. In addition to these, the lowest transfer time for Product 3 is obtained by MINWAL(W)-based first approach with different wminsup values (0.07 and 0.08). Finally, the lowest transfer time for Product 4 is obtained by MINWAL(O)-based approach (wminsup=0.3 and 0.4), MINWAL(W)-based first and second approaches (wminsup=0.04) and WARM-based approach. On the other hand, the lowest waiting time in queue for Product1, Product2 and Product3 is obtained by the WARM-based approach, while the lowest waiting time in queue for Product4 is obtained by

MINWAL(W)-based first approach with different wminsup values (0.07 and 0.08). As concluded from Table 4.31, a high number of products are waiting in the queue in the solution obtained by the WARM-based approach. Facility layouts, corresponding approach and wminsup threshold values are presented in Table 4.32.

Table 4.29 Cycle times (min)

Product	Layout 1	Layout 2	Layout 3	Layout 4	Layout 5
Product 1	79.098	86.671	73.285	73.542	74.787
Product 2	51.171	55.893	47.213	47.804	48.232
Product 3	81.049	69.190	70.382	64.973	64.669
Product 4	64.285	69.931	59.189	59.716	60.044
average time between any consecutive products	16.642	17.183	15.163	14.998	15.095

Table 4.30 Transfer time (min)

Product	Layout 1	Layout 2	Layout 3	Layout 4	Layout 5
Product 1	9.156	16.482	10.987	9.156	9.156
Product 2	19.551	19.551	16.758	13.965	13.965
Product 3	34.482	34.482	28.735	34.482	34.482
Product 4	83.331	66.664	83.331	66.664	83.331

Table 4.31 Waiting time in queue (min)

Product	Layout 1	Layout 2	Layout 3	Layout 4	Layout 5
Product 1	45.202	40.641	35.943	34.242	34.787
Product 2	51.485	50.527	47.458	46.959	47.773
Product 3	43.769	29.057	33.200	26.482	26.824
Product 4	42.351	40.386	35.024	39.427	41.018

Table 4.32 Facility layouts, corresponding approach, wminsup threshold value

layout	Approach	wminsup threshold value
Layout 1	MINWAL(O)	0.2
Layout 2	MINWAL(O)	0.3 and 0.4
Layout 2	MINWAL(W)-based first and second approach	0.04
Layout 3	MINWAL(W)-based first approach	0.07 and 0.08
Layout 4	WARM	-
Layout 5	BWARM	-

4.1.5.1 Model Verification and Validation

Verification and validation are the processes to determine if generated simulation model correctly represents the real outputs. Generated simulation model is verified by tracing that model. All of the processes that occurs during the simulation run time is listed by the simulation software, PROMODEL. In addition to this, the debugger is used to test the processing of any logic in simulation model.

4.2 Case Study-II (15 Products, 30 Machines)

As stated previously, the second case study deals with the facility layout problem with 15 products and 30 machines. As in the first case study, a hypothetical production system is designed for this implementation. The products' routes are presented in Table 4.33. While demand patterns of the products (frequency of the arrivals) are reported in Table 4.34, the workspace is illustrated in Figure 4.9. As illustrated in the figure, the workspace consists of six rows and five columns. The stochastic processing times of the products are presented in Appendix C. The assumptions relating to the production system are as follows:

- Each machine can perform ten operation at most at a time,
- Each part may visit each machine only once,
- The processing times are known and stochastic in nature,
- There is no setup times for machines,
- All of the machines have the same dimensions,
- The process sequence of each product is known,
- Material transport distance between machines are calculated as a vertical linear and based on a centroid to centroid procedure.

Table 4.33 The product routes for case study-II

Products	Processing sequence																		
Product_1	1	2	3	4	5	8	9	10	11	13	14	15	16	20	28	29	30		
Product_2	1	2	3	9	10	11	8	19	20	21	22	23	24	25	26	27	28	29	30
Product_3	4	5	6	10	11	15	16	17	18	20	23	26	27	28	29	30			
Product_4	12	15	16	19	22	23	24	28	29	30									
Product_5	1	2	3	4	5	6	7	8	9	12	14	15	16	17	18				
Product_6	2	3	5	6	7	8	9	10	11	19	30								
Product_7	5	6	7	8	9	10	11	12	15	16	17	19	25	26	27	29	30		
Product_8	8	9	1	2	3	12	16	17	18	19	24	25	30						
Product_9	12	13	16	24	25	30													
Product_10	1	2	3	4	8	9	15	16	24	28									
Product_11	1	2	3	4	11	12	13	14	21	22	23	24	27	28	29	30			
Product_12	1	2	3	10	11	12	13	14	15	16	17	18							
Product_13	1	4	6	8	9	12	16	15	18	21	22	25	27						
Product_14	3	4	5	6	7	12	19	20	25	27	28	30							
Product_15	1	2	3	4	5	6	7	8	9	11	12	13	18	19	26	27	28	29	30

Table 4.34 Demand patterns of the products

Product	Frequency of the arrivals
Product_1	Exponential (10.35) min
Product_2	Exponential (6.65) min
Product_3	Exponential (7.76) min
Product_4	Exponential (8.28) min
Product_5	Exponential (2.01) min
Product_6	Exponential (15.53) min
Product_7	Exponential (7.76) min
Product_8	Exponential (7.45) min
Product_9	Exponential (6.21) min
Product_10	Exponential (7.45) min
Product_11	Exponential (6.65) min
Product_12	Exponential (4.66) min
Product_13	Exponential (3.11) min
Product_14	Exponential (2.33) min
Product_15	Exponential (3.73) min

Machine x	Machine x	Machine x	Machine x	Machine x
Machine x	Machine x	Machine x	Machine x	Machine x
Machine x	Machine x	Machine x	Machine x	Machine x
Machine x	Machine x	Machine x	Machine x	Machine x
Machine x	Machine x	Machine x	Machine x	Machine x
Machine x	Machine x	Machine x	Machine x	Machine x

Figure 4.9 The workspace for case study-II

4.2.1 Implementation of the MINWAL(O)-Based Approach

Implementations of the first and second stages of the MINWAL(O)-based approach are explained in the following.

4.2.1.1 Implementation of the First Stage

Step 1. *Determine the factors that affect facility layout.*

The location factors considered in this experiment are the same as the factors considered in case study-I. These are; quantity of demand, part-handling factor and efficiency of material handling equipment.

Step 2: *Weight all machines by using relevant method.*

As mentioned previously, we employ AHP to obtain the weights of the machines. Product weights with respect to their demands are reported in Table 4.35. Pairwise comparison matrices for part-handling factor and for efficiency of material handling equipment are given in Tables 4.36 and 4.37, respectively. While, pairwise comparison matrix for the factors is given in Table 4.38, calculation of the weights of the products is given in Table 4.39. Finally, the machine weights are presented in Table 4.40.

Table 4.35 Product weights

product	demand	normalized weight
Product_1	180	0.032
Product_2	280	0.050
Product_3	240	0.043
Product_4	225	0.040
Product_5	925	0.165
Product_6	120	0.021
Product_7	240	0.043
Product_8	250	0.045
Product_9	300	0.054
Product_10	250	0.045
Product_11	280	0.050
Product_12	400	0.072
Product_13	600	0.107
Product_14	800	0.143
Product_15	500	0.089
Total	5590	1.00

Table 4.36 Pairwise comparison matrix with respect to part- handling factor

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	weight
P1	1	3	1	1	1	2	3	2	3	2	3	3	2	1	2	0.106
P2	0.33	1	3	2	2	1	1	1	1	1	1	1	2	3	1	0.085
P3	1.00	0.33	1	1	1	2	3	2	3	2	3	3	2	1	2	0.094
P4	1.00	0.50	1.00	1	3	2	3	2	3	2	3	3	2	1	2	0.105
P5	1.00	0.50	1.00	0.33	1	2	3	2	3	2	3	3	2	1	2	0.090
P6	0.50	1.00	0.50	0.50	0.50	1	3	3	2	1	1	1	3	3	2	0.075
P7	0.33	1.00	0.33	0.33	0.33	0.33	1	2	2	1	2	2	1	2	1	0.054
P8	0.50	1.00	0.50	0.50	0.50	0.33	0.50	1	3	3	2	1	1	1	1	0.056
P9	0.33	1.00	0.33	0.33	0.33	0.50	0.50	0.33	1	4	3	1	1	1	1	0.051
P10	0.50	1.00	0.50	0.50	0.50	1.00	1.00	0.33	0.25	1	1	2	3	1	3	0.056
P11	0.33	1.00	0.33	0.33	0.33	1.00	0.50	0.50	0.33	1.00	1	1	2	3	2	0.048
P12	0.33	1.00	0.33	0.33	0.33	1.00	0.50	1.00	1.00	0.50	1.00	1	1	3	2	0.047
P13	0.50	0.50	0.50	0.50	0.50	0.33	1.00	1.00	1.00	0.33	0.50	1.00	1	2	4	0.048
P14	1.00	0.33	1.00	1.00	1.00	0.33	0.50	1.00	1.00	1.00	0.33	0.33	0.50	1	2	0.049
P15	0.50	1.00	0.50	0.50	0.50	0.50	1.00	1.00	1.00	0.33	0.50	0.50	0.25	0.50	1	0,036
consistency ratio 0.099																1.000

PI: product I

Table 4.37 Pairwise comparison matrix with respect to efficiency of material handling equipment

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	weight
P1	1	3	1	6	5	3	2	1	5	3	3	3	1	1	1	0.172
P2	0.33	1	3.00	0.50	0.50	1	2	3	1	1	1	1	3	3	3	0.063
P3	1.00	0.33	1	0.10	0.20	0.30	1	1	0.20	0.30	0.30	0.30	1	1	1	0.027
P4	0.17	2.00	10	1	1	2	3	6	1	2	2	2	6	6	6	0.124
P5	0.20	2.00	5.00	1.00	1	2	3	5	1	2	2	2	5	5	5	0.110
P6	0.33	1.00	3.33	0.50	0.50	1	1.50	3	0.60	1	1	1	3	3	3	0.062
P7	0.50	0.50	2.00	0.33	0.33	0.67	1	2	0.40	0.67	0.67	0.67	2	2	2	0.043
P8	1.00	0.33	1.00	0.17	0.20	0.33	0.50	1	0.20	0.33	0.33	0.33	1	1	1	0.028
P9	0.20	2.00	5.00	1.00	1.00	1.67	2.50	5.00	1	1.67	1.67	1.67	5	5	5	0.103
P10	0.33	1.00	3.33	0.50	0.50	1.00	1.50	3.00	0.60	1	1	1	3	3	3	0.062
P11	0.33	1.00	3.33	0.50	0.50	1.00	1.50	3.00	0.60	1.00	1	1	3	3	3	0.062
P12	0.33	1.00	3.33	0.50	0.50	1.00	1.50	3.00	0.60	1.00	1.00	1	3	3	3	0.062
P13	1.00	0.33	1.00	0.17	0.20	0.33	0.50	1.00	0.20	0.33	0.33	0.33	1	1	1	0.028
P14	1.00	0.33	1.00	0.17	0.20	0.33	0.50	1.00	0.20	0.33	0.33	0.33	1.00	1	1	0.028
P15	1.00	0.33	1.00	0.17	0.20	0.33	0.50	1.00	0.20	0.33	0.33	0.33	1.00	1.00	1	0.028
consistency ratio 0.097																1.000

PI: product I

Table 4.38 Pairwise comparison matrix for the factors

		Factors			
		1	2	3	Weight
Factors	1	1	3	5	0.619
	2	1/3	1	4	0.284
	3	1/5	¼	1	0.096
consistency ratio 0.07					

Table 4.39 Calculation of the weights of the products

the weight of first factor	the weight of second factor	the weight of third factor		the weight of factors	the weight of products
0.032	0.106	0.172		0.619	Product_1= 0.067
0.050	0.085	0.063		0.284	Product_2= 0.061
0.043	0.094	0.027		0.097	Product_3= 0.056
0.040	0.105	0.124			Product_4= 0.067
0.165	0.090	0.110			Product_5= 0.139
0.021	0.075	0.062			Product_6= 0.041
0.043	0.054	0.043			Product_7= 0.046
0.045	0.056	0.028	x		Product_8= 0.046
0.054	0.051	0.103			Product_9= 0.058
0.045	0.056	0.062			Product_10= 0.049
0.050	0.048	0.062			Product_11= 0.051
0.072	0.047	0.062			Product_12= 0.064
0.107	0.048	0.028			Product_13= 0.083
0.143	0.049	0.028			Product_14= 0.105
0.089	0.036	0.028			Product_15= 0.068

Table 4.40 The machine weights

machine	weight	normalized weight
1	0.627	0.045
2	0.585	0.042
3	0.690	0.050
4	0.617	0.045
5	0.521	0.038
6	0.537	0.039
7	0.398	0.029
8	0.600	0.043
9	0.600	0.043
10	0.334	0.024
11	0.453	0.033
12	0.725	0.053
13	0.307	0.022
14	0.320	0.023
15	0.569	0.041
16	0.673	0.049
17	0.350	0.025
18	0.455	0.033
19	0.434	0.031
20	0.289	0.021
21	0.195	0.014
22	0.261	0.019
23	0.234	0.017
24	0.332	0.024
25	0.399	0.029
26	0.231	0.017
27	0.470	0.034
28	0.524	0.038
29	0.415	0.030
30	0.665	0.048
Total	13.809	1

Step 3: *Determine wminsup*

In case study-II, we determine three different wminsup threshold values, as in the first case, to compare the effect of wminsup threshold value on facility layout. These wminsup values are 0.2, 0.3 and 0.4.

Step 4: *Determine size (k)*

As stated before, size (k) equals the largest number of machines that a product route includes. In our production system, the largest number of machine, 19, exist on the route of Product_2 and Product 15.

Step 5: *Assign 0 to " x"*

Step 6: *Put all machine(s)/machineset(s) in Table C_x*

Table C_0 is presented in the following.

Table C_0

Machines	1	2	3	4	5	6	7	8	9	10
Machines	11	12	13	14	15	16	17	18	19	20
Machines	21	22	23	24	25	26	27	28	29	30

Step 7: *Calculate W(Y,k) of all machine(s)/machineset(s) in Table C_x*

Calculated *W(Y,k)* values are presented in Appendix D.

Step 8: *Calculate B(Y,k) of all machine(s)/machineset(s) in Table C_x*

Calculated *B(Y,k)* values are given in Appendix E.

Step 9: Calculate SC value of all machines/machineset(s) in Table C_x and add SC value to C_x.

Table C_0

Machines	1	2	3	4	5	6	7	8	9	10
SC	9	9	10	8	7	7	5	9	9	6

Machines	11	12	13	14	15	16	17	18	19	20
SC	8	10	5	4	8	10	5	6	7	4

Machines	21	22	23	24	25	26	27	28	29	30
SC	3	4	4	6	6	4	7	8	7	11

Step 10: *Are there any machine(s)/machineset(s) to be pruned* in Table C_x? (Rule (i))

The counts of all machines, except machine 21, are greater than the result of their *B(Y,k)* values. However, SC value of machine 21 is smaller than its *B(21,19)* value, which is 5. Therefore, we go to step 11.

Step 11: *Prune some machine(s)/machineset(s) in Table* C_x

We prune machine 21 in Table C_0.

Step 12: *Put the remaining machine(s)/machineset(s) on Table* C_{x+1}

We must construct Table C_1 because x=0. Table C_1 is presented in the following.

Table C_1

Machines	1	2	3	4	5	6	7	8	9
Machines	11	12	13	14	15	16	17	18	19
Machines	22	23	24	25	26	27	28	29	30

Step 13: *Are there any machine(s)/machineset(s) to be joined in Table* C_{x+1}*?*

There are machines to be joined in Table C_1. So we go to step 14.

Step 14: *Join some machine(s)/machineset(s) in Table* C_{x+1} *and put the joined machine(s)/machineset(s) on Table* C_{x+2}.

Total 80 machinesets (with 2-level) are obtained by joining. Obtained machinesets are given in Table C_2.

Table C_2 Machinesets with 2-level.

	1	2	3	4	5	6	7	8	9	10
X	{2,3}	{1,2}	{8,9}	{15,16}	{29,30}	{3,4}	{5,6}	{10,11}	{28,29}	{4,5}

	11	12	13	14	15	16	17	18	19	20
X	{6,7}	{16,17}	{27,28}	{7,8}	{9,10}	{11,12}	{12,13}	{17,18}	{26,27}	{13,14}

	21	22	23	24	25	26	27	28	29	30
X	{14,15}	{21,22}	{22,23}	{23,24}	{24,25}	{9,12}	{12,15}	{12,16}	{16,24}	{18,19}

	31	32	33	34	35	36	37	38	39	40
X	{19,20}	{24,28}	{25,26}	{25,27}	{25,30}	{1,4}	{1,9}	{3,9}	{3,5}	{3,12}

	41	42	43	44	45	46	47	48	49	50
X	{3,10}	{4,8}	{4,11}	{4,6}	{5,8}	{6,10}	{6,8}	{7,12}	{8,11}	{8,19}

	51	52	53	54	55	56	57	58	59	60
X	{9,15}	{9,11}	{11,13}	{11,15}	{11,19}	{12,14}	{12,19}	{13,16}	{13,18}	{20,21}

	61	62	63	64	65	66	67	68	69	70
X	{15,18}	{16,20}	{16,19}	{17,19}	{18,20}	{19,30}	{19,25}	{19,24}	{19,26}	{14,21}

	71	72	73	74	75	76	77	78	79	80
X	{18,21}	{20,25}	{20,28}	{22,25}	{20,23}	{23,26}	{24,27}	{27,29}	{28,30}	{19,22}

Step 15: *Are there any machine(s)/machineset(s) to be pruned* in Table C_{x+2}? (Rule (ii)).

The subsets of Machinesets {14,21}, {18,21}, {20,21} and {21,22} do not exist in C_1. Therefore, the answer of this question is yes. Then, we go to step 16.

Step 16: *Prune some machine(s)/machineset(s) in Table* C_{x+2}

We prune machinesets {14,21}, {18,21}, {20,21} and {21,22} in Table C_2

Step 17: *Are there any machine(s)/machineset(s) to calculate its/their W(Y,k) in Table* C_{x+2} ?

The answer of this question is yes. Then, we go to Step 18.

Step 18: *Assign x=x+2.*

In this step, we assign that x= x+2. Therefore we will use the last table which is C_{x+2}

We will use the same method for the remaining passes until the answer of step 17 is no (no machineset can be found to be joined). *W(Y,k)* and *B(Y,k)* values for 1-level machinesets are given in Appendix F and G, respectively. Finally, the results are reported in Table 4.41. As can be seen from Table 4.41, only 2-level machinesets remain at the end of the algorithm.

Table 4.41 Associations between the machines

{2,3}	{1,2}	{8,9}	{15,16}	{29,30}	{3,4}	{5,6}	{10,11}	{28,29}	{4,5}
{6,7}	{16,17}	{27,28}	{7,8}	{9,10}	{11,12}	{12,13}	{17,18}	{26,27}	

4.2.1.2 Implementation of the Second Stage

We use the algorithms presented in Figures 3.2 and 3.3 to obtain the final layout. The final layout corresponding to threshold (wminsup) value of 0.2 is illustrated in Figure 4.10

25	24	16	15	6	5
26	23	17	14	7	4
27	22	18	13	8	3
28	21	19	12	9	2
29	30	20	11	10	1

Figure 4.10 Final facility layout for MINWAL(O)-based approach (wminsup=0.2)

The associations found between the machines for wminsup=0.3 are {2,3}, {1,2}, {8,9}, {15,16}, {29,30}, {3,4}, {5,6}, {10,11}, {28,29} and for wminsup=0.4 are {2,3}, {1,2}, {8,9} and {15,16}. Final facility layout corresponding to wminsup=0.3 and 0.4 are the same as the one illustrated in Figure 4.10.

4.2.2 Implementation of the MINWAL(W)-Based Approach

4.2.2.1 First Approach

We find the same associations between machines for wminsup=0.02 using MINWAL(W)-based approach as MINWAL(O) approach for wminsup=0.3. Similarly, the associations for wminsup=0.012 using MINWAL(W)-based approach are same as MINWAL(O) with wminsup=0.2. Therefore, the final facility layouts obtained by MINWAL(W)-based approach with wminsup=0.02 and 0.012 are the same as the layout in Figure 4.10

4.2.2.2 Second Approach

Calculated NWS values are given in Appendix K. Herein, we take wminsup=0.012. As can be seen in Appendix K, there are 11 machines to be pruned because of the fact that their NWS values are less than the wminsup value. These machines are 10, 7, 17, 24, 13, 14, 20 22, 23, 26 and 21. The 2-level machinesets, obtained by joining the remaining machines and considering "low-order superset" definition, and their NWS values are presented in Appendix L. The associated machines are given in Table 4.42.

Table 4.42 NWS values for the associated machines

machine pair (a+b)	weight (a+b)	Y= ((a+b)/2)	support count (SC)	Number of product (T)	X=SC/T	NWS=X*Y
{2,3}	0.0939	0.0469	9	15	0.6000	0.0282
{15,16}	0.0914	0.0457	8	15	0.5333	0.0244
{1,2}	0.0892	0.0446	8	15	0.5333	0.0238
{8,9}	0.0882	0.0441	8	15	0.5333	0.0235
{29,30}	0.0794	0.0397	7	15	0.4667	0.0185
{3,4}	0.0901	0.0451	6	15	0.4000	0.0180
{5,6}	0.0778	0.0389	6	15	0.4000	0.0156
{28,29}	0.0691	0.0345	6	15	0.4000	0.0138
{4,5}	0.0776	0.0388	5	15	0.3333	0.0129
{16,17}	0.0753	0.0376	5	15	0.3333	0.0125
{27,28}	0.0731	0.0365	5	15	0.3333	0.0122

The 3-level machinesets, obtained by joining the machinesets in Table 4.42 and considering “low-order superset” definition, and their calculated NWS values are given in Appendix M. Among the 3-level machinesets, only the machineset {2,3,4} has the association since its NWS value is higher than 0.012. We stop because of the fact that we found only one 3-level machineset. The final layout using MINWAL(W)-based second approach is given in Figure 4.11.

26	27	28	29	30	20
21	22	23	24	25	19
13	14	15	16	17	18
12	11	10	9	8	7
1	2	3	4	5	6

Figure 4.11 Final facility layout for MINWAL (W)-based approach (wminsup=0.012)

4.2.3 WARM Based-Approach

The calculated weight of the products and sorted machine pairs with descending order according to their weight value (List A) are given in Appendix H and Appendix I, respectively. The final layout obtained by using the proposed WARM-based approach is given in Figure 4.12.

21	22	23	24	25	20
30	29	28	27	26	19
13	14	15	16	17	18
12	11	10	9	8	7
1	2	3	4	5	6

Figure 4.12 Final facility layout for the proposed WARM-based approach

4.2.4 BWARM-based approach

The calculated *WS* values for each machine pair and sorted machine pairs with descending order according to their WS value (List A) are given in Appendix J. The final layout obtained by using the proposed BWARM-based approach is given in Figure 4.13.

21	22	23	24	20	19
30	25	15	16	17	18
29	28	11	12	13	14
26	27	10	9	8	7
1	2	3	4	5	6

Figure 4.13 Final facility layout for the proposed BWARM-based approach

4.2.5 Simulation Outputs

As in the first case study, we employ simulation in this study to evaluate and compare the final layouts obtained by the proposed approaches. The comparison is made in terms of general performance criteria for the facility layout problems. The simulation models are run by PROMODEL simulation software. The models are run for 480 hours, representing a three-month period (8 hours a day, 5 days per week, 4 weeks per month, 3 moth= 8 hours*5 days*4 weeks*3months=480 hours).

The amounts of product produced per unit time corresponding to different layouts for case study-I are illustrated in the figures presented in Appendix N. The model is run 100 times for each facility layout. In determining the number of replication, the warm up period is taken into consideration. Moving average values for each replication corresponding to different layouts for case study-II are illustrated in the figures presented in Appendix P. The common random numbers are used as variance reduction technique.

Facility layouts obtained by the proposed approaches are illustrated in Figure 4.14. Herein, five performance measures are employed. These measures are; machine utilization, total amount of products produced, cycle time, transfer time and waiting time in queue. Facility layouts, corresponding approach and wminsup threshold values are presented in Table 4.43.

Layout 1

25	24	16	15	6	5
26	23	17	14	7	4
27	22	18	13	8	3
28	21	19	12	9	2
29	30	20	11	10	1

Layout 2

26	27	28	29	30	20
21	22	23	24	25	19
13	14	15	16	17	18
12	11	10	9	8	7
1	2	3	4	5	6

Layout 3

21	22	23	24	25	20
30	29	28	27	26	19
13	14	15	16	17	18
12	11	10	9	8	7
1	2	3	4	5	6

Layout 4

21	22	23	24	20	19
30	25	15	16	17	18
29	28	11	12	13	14
26	27	10	9	8	7
1	2	3	4	5	6

Figure 4.14 Facility layouts obtained by the proposed approaches for case study-II

Table 4.43 Facility layouts, corresponding approach and wminsup threshold values

layout	approach	wminsup threshold value
Layout 1	MINWAL(O)	0.2, 0.3 and 0.4
Layout 1	MINWAL(W)-based first approach	0.02 and 0.012
Layout 1	MINWAL(W)-based second approach	0.02
Layout 2	MINWAL(W)-based second approach	0.012
Layout 3	WARM	-
Layout 4	BWARM	-

As reported in Table 4.45, there are no important differences among the layouts obtained by the proposed approaches in terms of machine utilization.

Table 4.45 Machine utilizations (%)

Machine	Layout 1	Layout 2	Layout 3	Layout 4
M29	30.923	32.289	32.201	32.422
M30	38.039	39.631	39.517	39.973
M20	10.366	10.873	10.838	10.888
M11	53.998	52.063	52.227	51.927
M10	26.734	26.340	26.517	26.185
M1	80.880	79.946	79.985	79.958
M2	82.772	81.838	81.860	81.746
M3	96.527	96.360	96.369	96.343
M4	86.980	86.289	86.328	86.253
M5	72.188	70.718	70.762	70.598
M9	92.927	92.588	92.596	92.539
M8	94.177	94.030	94.036	93.980
M7	86.288	85.260	85.357	84.947
M6	75.483	73.906	74.053	73.590
M12	62.661	59.930	60.037	60.159
M13	32.933	30.415	30.135	30.327
M14	76.466	74.464	74.473	74.849
M15	79.157	77.758	77.825	76.420
M19	26.019	27.215	27.136	27.392
M18	61.338	64.204	63.984	64.152
M17	27.780	29.751	29.661	29.225
M16	79.265	77.609	77.651	78.295
M21	26.527	27.759	27.685	27.732
M22	36.836	38.458	38.364	38.547
M23	23.478	24.457	24.382	24.679
M24	24.876	25.885	25.776	26.083
M28	32.007	33.449	33.351	33.537
M27	49.240	51.496	51.352	51.502
M26	33.103	34.752	34.514	34.702
M25	30.312	31.617	31.452	31.871

The amounts of products produced are given in Table 4.46. The highest total amount of product is obtained by facility layout created by the proposed BWARM-based approach.

Table 4.46 Amount of products produced

Product	Layout 1	Layout 2	Layout 3	Layout 4
Product 1	2026.67	2118.93	2109.36	2115.48
Product 2	3146.96	3289.98	3281.66	3283.02
Product 3	1357.12	1433.33	1428.08	1438.08
Product 4	2906.60	2982.35	2979.75	3076.85
Product 5	10396.46	10872.87	10833.33	10856.45
Product 6	914.10	961.12	959.97	965.29
Product 7	2931.52	3079.17	3071.52	3081.29
Product 8	134.38	146.17	146.55	154.18
Product 9	3882.33	3985.83	3971.38	4104.30
Product 10	2732.82	2860.04	2853.44	2855.08
Product 11	3153.02	3294.27	3281.31	3290.78
Product 12	4498.27	4699.60	4688.10	4693.74
Product 13	6740.83	7053.99	7033.64	7046.54
Product 14	500.22	525.93	528.51	535.90
Product 15	5606.65	5862.69	5839.79	5860.95
Total	50927.95	53166.27	53006.39	53357.93

Tables 4.47, 4.48 and 4.49 report the cycle time, transfer time and waiting time in queue of each product, respectively, corresponding to each layout type. From Table 4.47, it is clearly stated that the lowest "average time between any consecutive products" is obtained by layout 1 (MINWAL(O)-based approach with wminsup values of 0.2, 0.3 and 0.4). Additionally, the lowest transfer time is also obtained by Layout 1. Finally, the lowest waiting times in queue is obtained by Layout 4.

Table 4.47 Cycle times (min)

Product	Layout 1	Layout 2	Layout 3	Layout 4
Product 1	13.32601	13.43519	13.45514	13.42740
Product 2	8.58196	8.65239	8.64205	8.65714
Product 3	19.91695	19.89178	19.87986	19.78302
Product 4	9.29283	9.53777	9.51344	9.23606
Product 5	2.59442	2.61805	2.61965	2.61700
Product 6	29.50063	29.61385	29.63180	29.45470
Product 7	9.21888	9.24383	9.23966	9.22342
Product 8	209.14948	199.50506	198.06500	187.78828
Product 9	6.94547	7.13903	7.13965	6.92153
Product 10	9.88659	9.95011	9.93830	9.95189
Product 11	8.55172	8.64200	8.64935	8.63518
Product 12	5.99585	6.05494	6.04979	6.05435
Product 13	4.00124	4.03410	4.03367	4.03250
Product 14	53.98429	54.49870	53.95950	53.35044
Product 15	4.81607	4.85354	4.85507	4.84833
average time between any consecutive products	0.53031	0.53535	0.53531	0.53259

Table 4.48 Transfer time (min)

Product	Layout 1	Layout 2	Layout 3	Layout 4
Product 1	2.56608	2.484	2.484	2.700
Product 2	4.80546	6.476	5.462	6.273
Product 3	6.16572	6.228	5.979	5.979
Product 4	2.19582	2.218	2.349	2.349
Product 5	2.21364	2.536	2.536	2.685
Product 6	2.80566	3.708	4.364	4.364
Product 7	7.39728	6.068	6.536	7.784
Product 8	8.87337	7.527	9.322	7.168
Product 9	2.11662	1.359	2.333	1.165
Product 10	4.02831	3.051	3.306	3.815
Product 11	6.44589	5.425	5.153	7.327
Product 12	3.52638	3.014	3.014	3.836
Product 13	9.83862	13.121	12.723	9.539
Product 14	8.17146	10.220	9.041	8.253
Product 15	10.23957	13.166	10.813	12.696

Table 4.49 Waiting time in queue (min)

Product	Layout 1	Layout 2	Layout 3	Layout 4
Product 1	15.885	15.545	15.516	15.329
Product 2	12.545	12.519	12.504	12.419
Product 3	3.054	2.949	2.916	2.708
Product 4	1.738	1.530	1.524	1.462
Product 5	17.935	17.626	17.610	17.260
Product 6	13.590	13.536	13.488	13.346
Product 7	12.379	12.050	12.017	11.779
Product 8	5.417	5.531	5.570	5.229
Product 9	0.788	0.723	0.718	0.574
Product 10	14.847	14.573	14.523	14.333
Product 11	6.130	6.022	5.973	5.977
Product 12	6.884	6.630	6.586	6.410
Product 13	12.378	12.140	12.068	11.771
Product 14	3.725	3.731	3.685	3.558
Product 15	15.578	15.600	15.546	15.289

4.2.5.1 Model Verification and Validation

Like the first case study, generated simulation model for case study-II is verified by tracing the simulation model. In addition to this, the debugger is used to test the processing of any logic in simulation model. Therefore, any error during simulation is captured easily.

4.3 Conclusion

In this chapter, the proposed approaches are applied to two different case studies in order to confirm their viability by using simulation. The general performance measurement criteria for the facility layout problems, namely machine utilization, total amount of products produced, cycle time, transfer time and waiting time in queue are used to compare the characteristics of the layouts. In case study-I, proposed WARM-based approach provides better results in terms of total amount of products produced, cycle time, waiting time in queue and transfer time. In case study-II, all layouts obtained by the proposed approaches give similar results. The results obtained by simulation for case study-II are almost equal to each other. There are no important differences among them in terms of the general performance measurement criteria considered.

CHAPTER FIVE
CONCLUSION AND FUTURE RESEARCH

5.1 Conclusion

This study proposes five different weighted association rule-based data mining approaches for facility layout problem. To our knowledge, this is the first study that applies weighted association rule-based data mining approaches to facility layout problem. Three location factors, namely demand, part handling factor and efficiency of material handling equipment that are most pertinent to facility layout problems are selected as the weighting criteria. This study differs from the previous works in two ways. First, it considers these three key location factors together. Second, in addition to the quantitative factors, a qualitative factor is considered in algorithmic approaches.

The proposed approaches are based on MINWAL(O), MINWAL(W), WARM and BWARM approaches. Facility layouts obtained by the proposed approaches are compared in terms of five performance measures, namely machine utilization, total amount of products produced, cycle time, transfer time and waiting time in queue, using simulation. The results indicate that the proposed WARM-based approach provides better results in terms of total amount of products produced, cycle time, waiting time in queue and transfer time for case study-I. However, the proposed approaches provide similar results for case study-II.

The proposed MINWAL(O)-based and MINWAL(W)-based approaches can give same or different layout configuration according to the weighted minimum support value (wminsup) used. The proposed two MINWAL(W)-based approaches can also give different layout configurations even using the same wminsup value.

5.2 Future Research Directions

By means of the approaches proposed in this study, quantitative and qualitative factors that affect facility layout can be taken into account. In this concern, the following works can be regarded as future research directions.

- The proposed approaches can be applied to multiobjective facility layout problems.
- Other weighting methods such as SAW, LAM, TOPSIS, ELECTRE etc. can be used for weighting the facilities, and the results can be compared.
- Other production factors such as batch sizes, processing time learning rate, operation costs, inventory costs and machine breakdowns can be considered.
- Facility layout problem can be treated by considering the ergonomic factors.

REFERENCES

Abdou, G., & Dutta, S.P. (1990). An integrated approach to facilities layout using expert system. *International Journal of Production Research*. 28(4), 685-708.

Abduelmula, A., & Wagner, C. (2004). Design and evaluation of lean manufacturing cells: A simulation model. *IAMOT 2004* - Washington, D.C.

Afentakis, P., Millen, R.A., & Solomon, M.M. (1990). Dynamic layout strategies for flexible manufacturing systems. *International Journal of Production Research*. 28(8), 311-323.

Armour, G.C., & Buffa, E.S. (1963). A heuristic algorithm and simulation approach to relative location of facilities. *Management Science*. 4(2), 294-309.

Assad A. A., Kramer S. B., & Kaku B. K. (2003). Comparing functional and cellular layouts: A simulation study based on standardization. *International Journal of Production Research*. 41(8), 1639-1663.

Balakrishnan, J., Cheng, C.H., & Wong, K.F. (2003). FACOPT: a user friendly facility layout optimization system, *Computers & Operations Research*, 30, 1625–1641.

Banerjee, P., Montreuil, B., Moodie, C.L., & Kashyap, R.L. (1992). A modeling of interactive facilities layout designer reasoning using qualitative patterns. *International Journal of Production Research* 30(3):433–453.

Bin S., Min Y.,& Bo Y. (2005). Mining weighted generalized fuzzy association rules with fuzzy taxonomies. *LNAI 3801*, CIS 2005, Part I, 704 – 712.

Block, T.E. (1978). FATE: A New Construction Algorithm for Facilities Layout. *Journal of Engineering. Production*, 2, 111-120.

Brandeau, M.L., & Chiu, S.S. (1989). An overview of representative problems in location research. *Management Science*, 35(6), 645-674.

Bozer, Y.A., Meller, R.D., & Erlebacher, S.J. (1994). An improvement-type layout algorithm for single and multiple-floor facilities. *Management Science*, 40(7), 918-932.

Buffa, E.S., Armour, G.C., & Vollman, T.E. (1964). Allocating facilities with CRAFT. *Harvard Business Review*, 42, 1964, 136-158.

Cai C.H., Fu A.W.C., Cheng C.H., & Kwong W.W. (1998). Mining association rules with weighted items. *In: Proceedings of the international Database Engineering and Application Symposium*, Cardiff, UK, 68-77.

Camp, V.D.J., Carter, M.V., & Vannelli, A. (1992). A nonlinear optimization approach for solving facility layout problems. *European Journal of Operational Research,* 57(2), 174-189

Canen, A.G., & Williamson, G.H. (1998). Facility layout overview: Towards competitive advantage. *Facilities*, 16(7/8), 198-203.

Chan, W.M., Chan, C.Y., & Ip, W.H. (2002). A heuristic algorithm for machine assignment in cellular layout. *Computers & Industrial Engineering*, 44, 49-73.

Chen, M.C. (2003). Configuration of cellular manufacturing systems using association rule induction. *International Journal of Production Research.* 41(2), 381-395.

Chien T.K., (2004). An empirical study of facility layout using a modified SLP procedure. *Journal of Manufacturing Technology Management*, 15(6), 455-465.

Choudhary, A.K., Harding, J.A., & Tiwari, M.K. (2009). Data mining in manufacturing: A review based on the kind of knowledge. *Journal of Intelligent Manufacturing*, 20, 501-521.

Chung, Y.K. (1999). A neuro-based expert system for facility layout construction. *Journal of Intelligent Manufacturing*, 10, 359-385.

Current, J., Min, H., & Schilling, D. (1990). Multiobjective analysis of facility location decisions. *European Journal of Operational Research*, 49, 295-307.

Deisenroth, M.P., & Apple, J.M. (1972). A computerized plant layout analysis and evaluation technique (PLANET), in, Technical Papers, No. 1962, *American Institute of Industrial Engineers*, Norcross, GA.

Donaghey, C. E., & Pire, V. F. (1991). *Solving the Facility Layout Problem with BLOCPLAN,* Factory Automation and Information Management, CRC Press.

Drezner, Z.(1980). DISCON: a new method for the layout problem. *Operations Research*, 28(6), 1375-1385.

Drira, A., Pierreval, H., & Hajri-Gabouj, S. (2007). Facility layout problems: A survey. *Annual Reviews in Control*, 31, 255-267.

Domschke, W., & Krispin G. (1997). Location and layout planning A survey. *OR Spektrum*, 19, 181-194.

Dua S., Singh H., & Thompson H.W. (2009). Associative classification of mammograms using weighted rules. *Expert Systems with Applications*, 36, 9250-9259.

Dunham, M.H. (2003). *Data Mining introductory and advanced topics.* U.S.A: Pearson Education.

Edwards, H.K., Gillett, B.E., & Hale, M.E. (1970). Modular Allocation Technique (MAT). *Management Science,*17(3), 161-169.

Farahani, R.Z., Seifi, M.S., & Asgari, N. (2010). Multiple criteria facility location problems: A survey. *Applied Mathematical Modelling*, 34, 1689-1709.

Felix, T.S., Chan, & Abhary, K., (1996). Design and evaluation of automated cellular manufacturing systems with simulation modelling and AHP approach: A case study. *Integrated Manufacturing Systems*, 7(9), 39-52.

Forsati, R., & Meybodi, M.R. (2010). Effective page recommendation algorithms based on distributed learning automata and weighted association rules. *Expert Systems with Applications*. Article in press. DOI: 10.1016/j.eswa.2009.06.010

Foulds, L. R., & Robinson, D. F. (1976). A strategy for solving the plant layout problem. Operational Research Quarterly, 27(4), 845-855.

Gopalakrishnan, B., Weng, L.,& Gupta, D.P. (2003). Facilities design using a split departmental layout configuration. *Facilities.* 21(3/4), 66-73.

Ge J., Qiu, Y., Chen, Z., & Yin, S. (2008). Technology of information push based on weighted association rules mining. *Fifth International Conference on Fuzzy Systems and Knowledge Discovery*, 615-619.

Han, J., & Kamber, M. (2001). *Data mining: Concepts and techniques*. U.S.A: Morgan Kamufmann.

Harding, J.A., Shahbaz, M., Srinivas, & Kusiak, A. (2006). Data mining in manufacturing: A review. *Journal of Manufacturing Science and Engineering*. 128, 969-976.

Hassan, M.M.D. (1994). Machine layout problem in modern manufacturing facilities. *International Journal of Production Research*, 31(11), 2559-2584.

Hassan, M.M.D., Hogg, G.L., & Smith, S.R. (1986). SHAPE: A construction algorithm for area placement evaluation. *International Journal of Production Research*, 24(5), 1283-1295.

Heragu, S.S., & Kusiak, A. (1998). Machine layout problem in flexible manufacturing system. *Operations Research*, 36(2), 258-268.

Hillier, F.S.(1963). Quantitative tools for plant layout analysis. *Journal of Industrial Engineering*, 14, 33-40.

Hillier, F.S., & Connors, M.M. (1966). Quadratic Assignment problem algorithms and the location of indivisible facilities. *Management Science*, 13, 42-57.

Hipp, J., Guntzer, U., & Nakhaeizadeh, G. (2000). Algorithms for association rule mining-A general survey and comparison. *ACM SIG KDD Explorations*, 2(1), 58-64.

Ismail, R., Othman, Z., & Abu Bakar, A. (2009). Data mining in production planning and scheduling: A review. *2nd Conference on Data Mining and Optimization* 27-28 October, Selangor, Malaysia.

Jajodia, S., Minis, I., Harhalakis, G., & Proth, J.M. (1992). CLASS: computerized layout solutions using simulated annealing, *International Journal of Production Research*, 30(1), 95-108.

Jeong, K.C., & Kim, Y.D. (1998). A real-time scheduling mechanism for a Flexible manufacturing system: using simulation and dispatching rules. *International Journal of Production Research*, 36(9), 2609- 2626.

Jian, W., & Ming, L.X. (2008). An effective mining algorithm for weighted association rules in communication networks. *Journal of Computers*, 3(10),20-27.

Jiang H., Zhao Y., Yang C., &Dong X. (2008). Mining both positive and negative weighted association rules with multiple minimum supports. *International Conference on Computer Science and Software Engineering*, 407-410.

Jithavech, I. (2008). *Facility layout design considering risk for single-period and multi-period cases.* PhD Thesis, Whichita State University. Department of Industrial and Manufacturing Engineering. Kansas, U.S.A.

Johnson, R.V. (1982). Spacecraft for multi-floor layout planning. *Management Science*, 28(4), 407-417.

Kamrani, A.K., Hubbard, K., Parsaep, H.R., & Leew, H.R. (1998). Simulation-based methodology for machine cell design, *Computers & Industrial Engineering*, 34(1), 173-188

Kaya, M., & Alhajj, R. (2008). Online mining of fuzzy multidimensional weighted association rules. *Applied Intelligence*, 29, 13-34.

Kaya, M., & Alhajj, R. (2006a). Utilizing genetic algorithms to optimize membership functions for fuzzy weighted association rules mining. *Applied Intelligence*, 24, 7-15.

Kaya, M., & Alhajj, R. (2006b). Effective mining of fuzzy multi-cross-level weighted association rules. *ISMIS 2006*, LNAI 4203, 399-408.

Kaya, M., & Alhajj, R. (2006c). Extending olap with fuzziness for effective mining of fuzzy multidimensional weighted association rules. *ADMA 2006, LNAI 4093*, 64–71.

Khalil, T.M. (1973). Facilities relative allocation technique (FRAT), *International* Journal *of Production Research*, 11(2), 183-194.

Khan, M.S., Muyeba, M., & Coenen, F. (2008). Weighted association rule mining from binary and fuzzy data. *ICDM 2008, LNAI, 5077*, 200–212.

Krishnan, K.K., Jithavech, I., & Liao, H. (2009). Mitigation of risk in facility layout design for single and multi-period problems. *International Journal of Production Research*, 47(21), 5911-5940.

Kochhar, J.S., & Heragu, S. S. (1998). MULTI-HOPE: a tool for multiple floor layout problems, *International Journal of Production Research*, 36(12) , 3421-3435.

Kochhar, J.S., Foster, B.T., & Heragu, S.S. (1998). HOPE: A genetic algorthm for the unequal area facility layout problem. *Computers & Operations Research*, 25(7/8), 583-594.

Koopmans, T.C., & Beckman, M. (1957). Assignment problems and the location of economic activities. *Econometrica*, 25, 53-76.

Koren, Y., Heisen, U., Jovane, F., Moriwaki, T., Pritschow, G., Ulusoy, G., & Brussel, H.V. (1999). Reconfigurable manufacturing system. *Annals of the CIRP*, 48(2), 527-540.

Kotsiantis, S., & Kanellopoulos, D. (2006). Association rules mining: a recent overview. *GESTS International Transactions on Computer Science and Engineering*, 32(1), 71-82.

Kusiak A. (2006). Data mining: manufacturing and service applications. *International Journal of Production Research*, 44, 18–19, 4175-4191.

Kusiak, A., & Heragu, S.S. (1987). The facility layout problem. *European Journal of Operational Research,* 29,229-251.

Law, A.M., & McComas, M.G. (1997). Simulation of manufacturing systems. *Proceedings of the 1997 Winter Simulation Conference*, 86-89.

Li, T., & Hailin Xiao, X.L. (2007). An effective algorithm for mining weighted association rules in telecommunication networks. *International Conference on Computational Intelligence and Security Workshop*s, 425- 428.

Lee, R.C., & Moore, J.M. 1967. CORELAP - Computerized Relationship Layout Planning. *Journal of Industrial Engineering*, 18, 195-200.

Liggett, R.S. (2000). Automated facilities layout: past, present and future. *Automation in Construction,* 9, 197–215.

Liu, C., Yasuda, K., Yin, Y., & Tanaka, K. (2009). Uncertain association rule mining algorithm for the cell formation problem in cellular manufacturing systems. *International Journal of Production Research*, 47(3), 667–685.

Lu, S., Hu, H., & Li, F. (2001). Mining weighted association rules. *Intelligent Data Analysis*, 5, 211-225.

Mahamaneerat, W.K., Shyu, C.R., Ho, S.C., & Chang, C.A. (2007). Domain-concept association rules mining for large-scale and complex cellular manufacturing tasks. *Journal of Manufacturing Technology Management*, 18(7), 787-806.

Marcoux, N. , Riopel, D., & Langevin, A.(2005). Models and Methods for Facilities Layout Design from an Applicability to Real-World Perspective. In A. Langevin and D.Riopel (Ed.). *Logistics Systems: Design and Optimization* (123-170). New York: U.S.A.

Matsuzaki, K., Irohara, T., & Yoshimoto, K. (1999). Heuristic algorithm to solve the multi-foor layout problem with the consideration of elevator utilization. *Computers & Industrial Engineering*, 36, 487-502.

Mei, Y., & Zhu, L. (2008). Risk analysis of the association rules in the incremental mining based on the weighted model. *International Conference on Computer Science and Information Technology*, 662-664.

Meller, R.D., & Bozer, Y.A. (1996). A new simulated annealing algorithm for the facility layout problem. *International Journal of Production Research* 34(6) 1675–1692.

Meller, R.D., & Bozer, Y.A. (1997). Alternative Approaches to solve the multi- floor facility layout problem. *Journal of Manufacturing System*, 16(3), 192-203.

Meller, R., & Gau, K.Y. (1996). The facility layout problem: recent and emerging trends and perspectives. *Journal of Manufacturing Systems*, 15(5), 351-366.

Montreuil, B., Ratliff, H.D., Goetschalckx, M. (1987). Matching Based Interactive Facility Layout. *IIE Transactions,* 19(3), 271 – 279.

Morris, J.S., & Tersine, R.J. (1990). A simulation analysis of factors influencing the attractiveness of group technology cellular layouts. *Management Science*, 36(12), 1567- 1578.

Mosier, C.T., Elvers, D.A., & Kelly, D. (1984). Analysis of group technology scheduling heuristics. *International Journal of Production Research*, 22(5), 857-875.

Muther, R. (1973). Systematic Layout Planning. 2 nd ed., Cahners Book, Boston:MA.

Nugent, C.E., Vollmann, T.E. & Ruml, J., (1968). An experimental comparison of techniques for the assignment of facilities to locations. *Operations Research*, 16(1), 150-173.

O'Brien, C., & Barr, S.E.Z.A.(1980). An interactive approach to computer aided facility layout. *International Journal of Production Research*, 18(2), 201-211.

Ramaraj, E., & Venkatesan, N. (2008). Positive and negative association rule analysis in health care database. *International Journal of Computer Science and Network Security*, 8(10), 325-330.

Roiger, R.J., & Geatz, M.W. (2003). *Data mining a tutorial-based primer*. U.S.A: Pearson Education.

Satty, T.L. (1994). How to make a decision: The analytic hierarchy process. *Interfaces*, 24(6), 19-43.

Scriabin, M., & Vergin R.C. (1975). Comparison of computer algorithms and visual based methods for plant layout. *Management Science*, 22(2), 172-181.

Shahbaz, M., Srinivas, Harding J,A., & Turner M. (2006). Product design and manufacturing process improvement using association rules. *Journal of Engineering Manufacture*, 220, Part B, 243-254.

Shambu, G., & Suresh, N.C. (2000). Performance of hybrid cellular manufacturing systems: a computer simulation investigation. *European Journal of Operational Research*, 20, 436-458.

Sheehof, J.M., & Evans, W. 0.(1967). Automatic Layout Design Program. *The Journal of Industrial Engineering*, 18, 690- 695.

Singh, S.P., & Sharma, R.R.K. (2006). A review of different approaches to the facility layout problems. *The International Journal of Advanced Manufacturing Technology*, 30, 425-433.

Snyder, L.V. (2006). Facility location under uncertainty: a review, *IIE Transactions*, 38, 537-554.

Sule, D.R.(1994). *Manufacturing facilities: Location, planning and design*. U.S.A: PWS Publishing.

Sumathi, S., & Sivanandam, S.N. (2006). *Introduction to data mining and its applications*. Berlin Heidelberg New York: Springer.

Sun, K., & Bai, F. (2008). Mining weighted association rules without pre assigned weights. *IEEE Transactions on Knowledge and Data Engineering*, 20(4), 489-495.

Tam, K.Y. (1992). A Simulated Annealing Algorithm for Allocating Space to Manufacturing Cells," *International Journal of Production Research* , 30, 63-87.

Tao, F., Murtagh, F., & Farid, M. (2003). Weighted association rule mining using weighted support and significance framework. *Proceedings of the ninth ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*, 661-666.

Tate, D.M. & Smith, A.E. (1995).Unequal-area facility layout by genetic search, *IIE Transactions*, 27(4), 465 – 472.

Tompkins, J.A., & Reed, R.J. (1976). An applied model for the facilities design problem. *International Journal of Production Research*, 14(5), 583-595

Tompkins, J.A., White, J.A., Bozer, Y.A., Frazelle, E.H., Tanchoco, J.M.A., & Trevino, J. (1996). *Facilities Planning*. New York: John Wiley.

Ulutas, B. (2008). *A clonal selection algorithm to solve dynamic facility layout problem and applications.* Eskisehir Osmangazi University. Department of Industrial Engineering. PhD Thesis, Eskisehir Osmangazi University, Eskisehir, Turkey.

Vercellis, C. (2009). Business *intelligence: Data mining and optimization for decision making*. United Kingdom: John Wiley & Sons.

Yue, S. J., Tsang, E., Yeung, D., & Shi, D. (2000). Mining fuzzy association rules with weighted items. *IEEE*. 1906-1911.

Wang, B.Y., & Zhang, S.M. (2003). A mining algorithm for fuzzy weighted association rules. *Proceedings of the second international conference on machine learning and cybernetics*, Wan, 2495-2499.

Wäscher, G., & Merker, J. (1997). A comparative evaluation of heuristics for the adjacency problem in facility layout planning. *International Journal of Production Research*, 35(2), 447-466.

Yang, T., & Hung, C.C. (2007). Multiple-attribute decision making methods for plant layout design problem. *Robotics and Computer-Integrated Manufacturing*, 23, 126–137.

Yang, T., & Kou, C. (2003). A hierarchical AHP/DEA methodology for the facilities layout design problem. *European Journal of Operational Research*, 147, 128–136.

Yun, U. (2007). Efficient mining of weighted interesting patterns with a strong weight and/or support affinity. *Information Sciences*, 177, 3477-3499.

Yun, U. (2008). An efficient mining of weighted frequent patterns with length decreasing support constraints. *Knowledge-Based Systems*, 21, 741–752.

Zolfaghari, S., & Lopez Roa, E.V. (2006). Cellular manufacturing versus a hybrid system: a comparative study. *Journal of Manufacturing Technology Management*, 17(7), 942-961.

Zhao, Q., & Bhowmick, S.S. (2003). *Association rule mining: a survey*. Technical Report, CAIS, Nanyang Technological University, Singapore, (No. 2003116.)

Zhou, N., Wu, J.X., Zhang, S.L., Chen, H.Q., & Zhang, X.R. (2007). Mining weighted association rules with lucene index. *IEEE.*, 3697-3700.

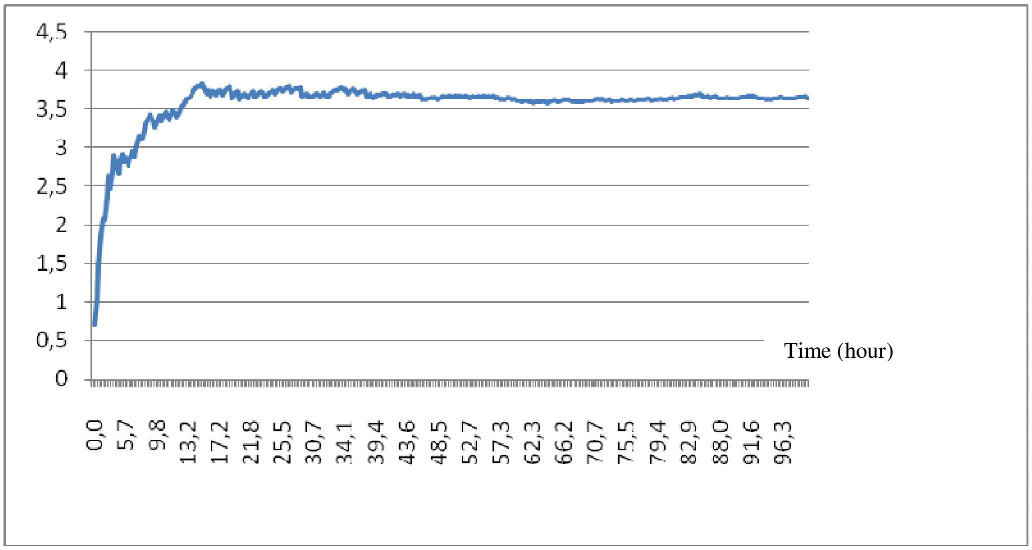
Zhu, H., & Xu, Z. (2008). An effective algorithm for mining positive and negative association rules. *International Conference on Computer Science and Software Engineering*, 455-458.

APPENDICES

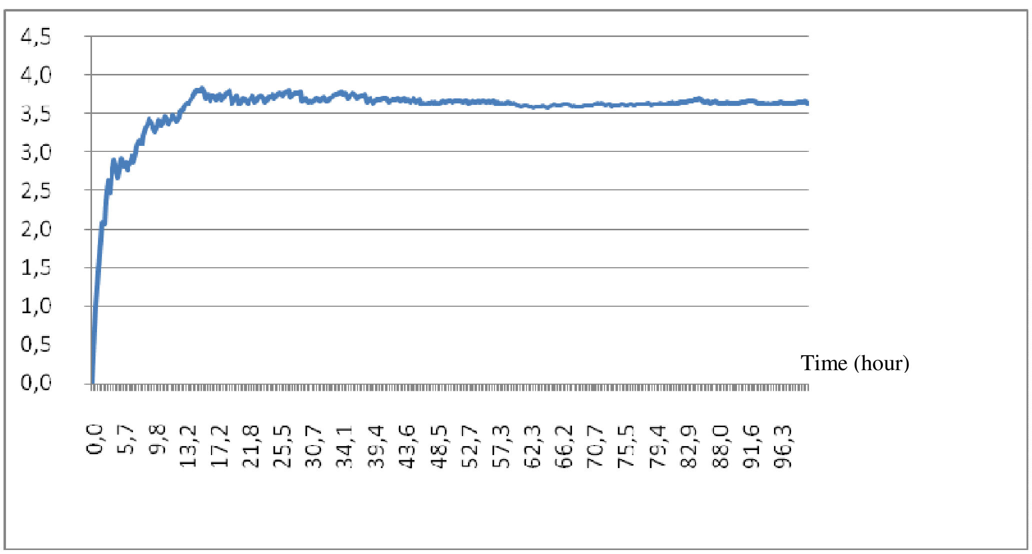
Appendix A

The amount of product produced per unit time corresponding to different layouts for case study-I

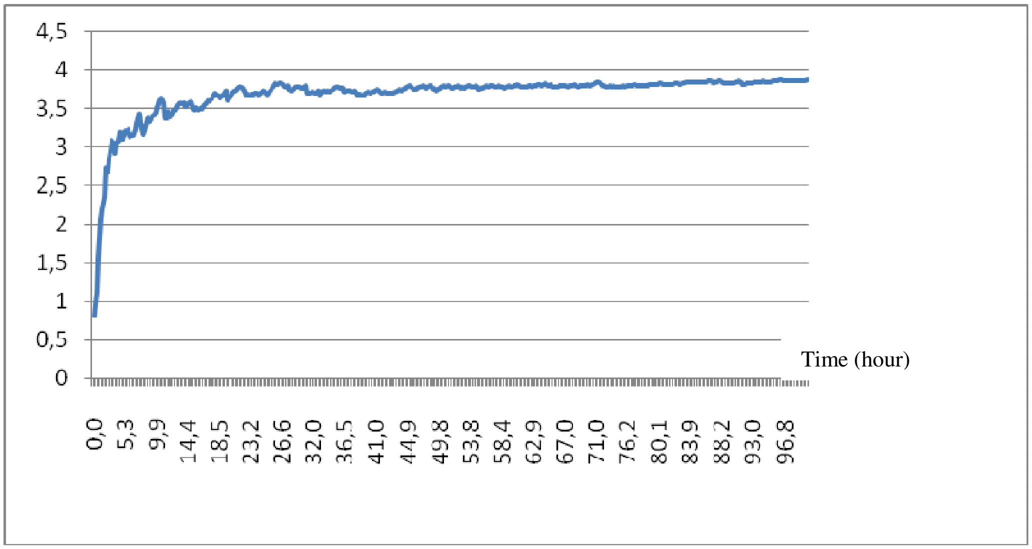
A1. The amount of product corresponding to layout 1



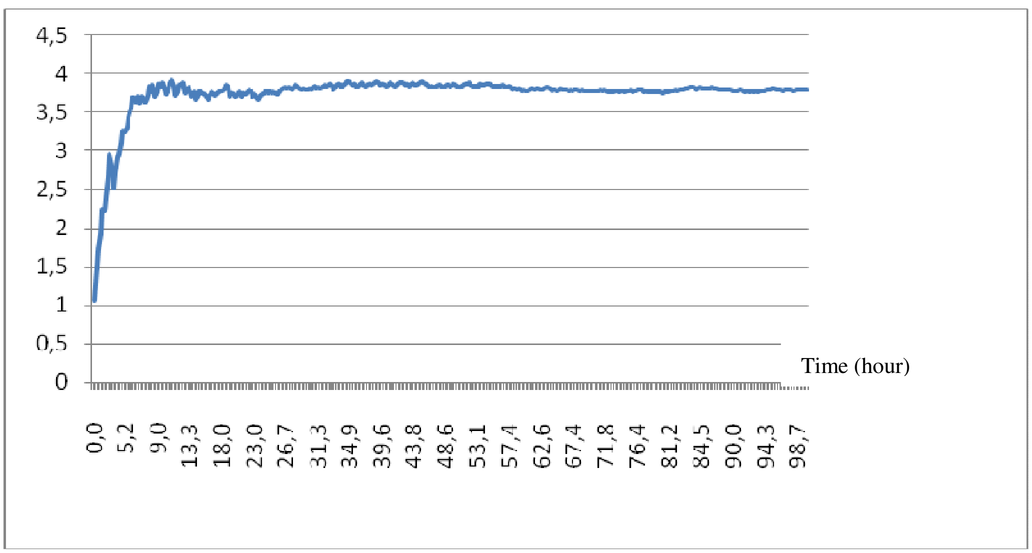
A2. The amount of product corresponding to layout 2



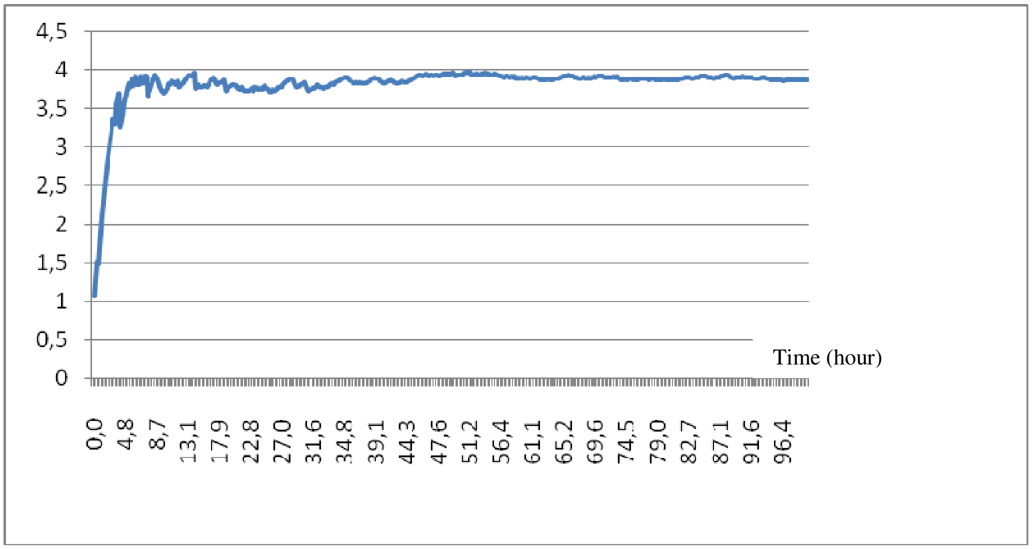
A3. The amount of product corresponding to layout 3



A4. The amount of product corresponding to layout 4



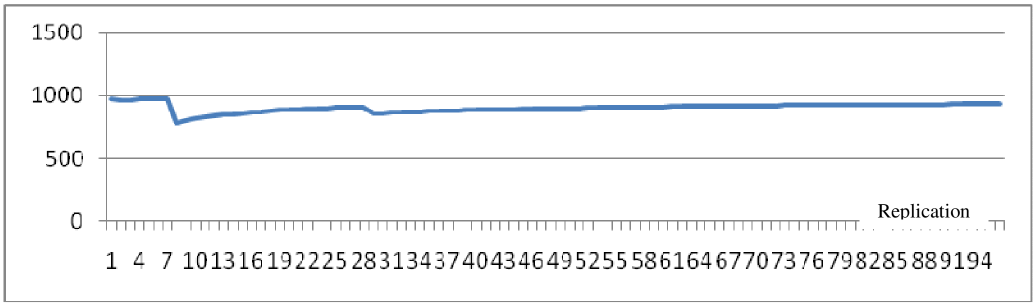
A5. The amount of product corresponding to layout 5



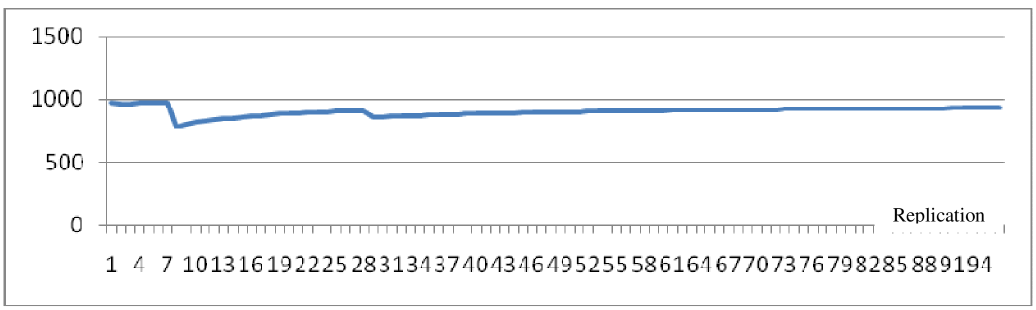
Appendix B

Moving averages of the amount of production for each replication corresponding to different layouts for case study-I

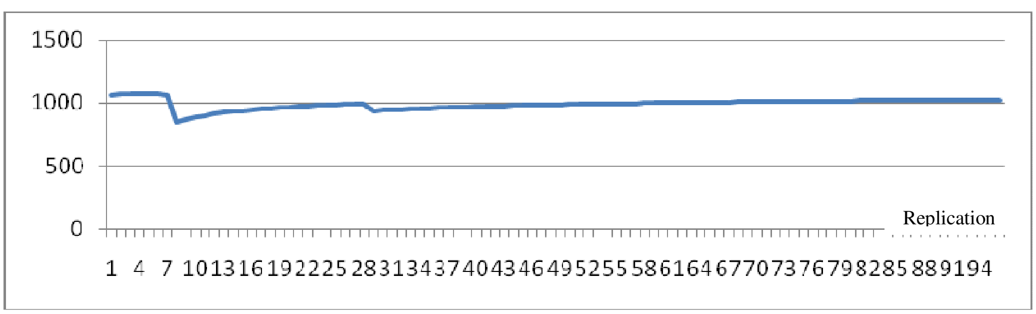
B1. Moving averages of the amount of production corresponding to layout 1



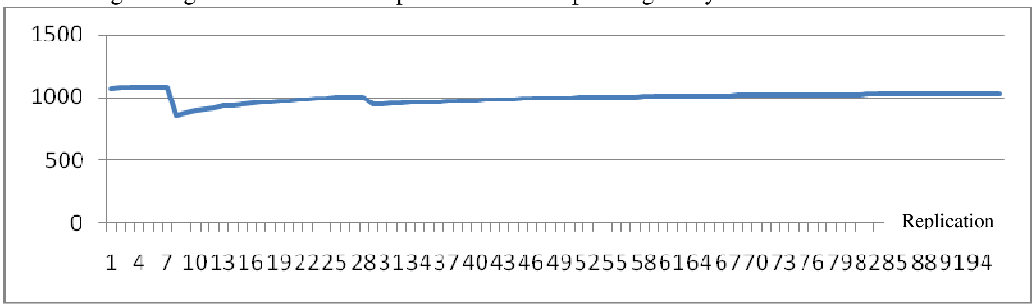
B2. Moving averages of the amount of production corresponding to layout 2



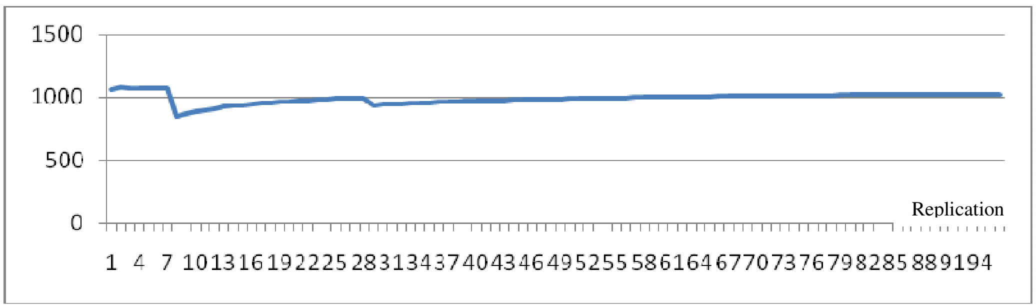
B3. Moving averages of the amount of production corresponding to layout 3



B4. Moving averages of the amount of production corresponding to layout 4



B5. Moving averages of the amount of production corresponding to layout 5



Appendix C

Processing times of the products for case study-II

C. Processing times of the products

Product	Machine	Distribution (min)
Product_1	1	N(4.1; 2)
Product_1	2	N(3; 0.9)
Product_1	3	N(6; 0.3)
Product_1	4	N(4.2; 1.2)
Product_1	5	N(6.4; 2.2)
Product_1	8	N(2; 0.5)
Product_1	9	N(5; 1.2)
Product_1	10	N(2.3; 0.3)
Product_1	11	N(4.8; 1.3)
Product_1	13	N(3.3; 1.2)
Product_1	14	N(8; 1.8)
Product_1	15	N(4; 1.2)
Product_1	16	N(3.3; 1.1)
Product_1	20	N(6; 2)
Product_1	28	N(1.5; 0.2)
Product_1	29	N(6.7; 1.7)
Product_1	30	N(2.6; 1.1)
Product_2	1	N(5; 1.2
Product_2	2	N(3.4; 1.2)
Product_2	3	N(6; 2)
Product_2	9	N(3; 0.8)
Product_2	10	N(5; 1.2)
Product_2	11	N(3.9; 1.1)
Product_2	18	N(7.2; 2.8)
Product_2	19	N(4.4; 1.2)
Product_2	20	N(2.1; 0.9)
Product_2	21	N(3.3; 1.2)
Product_2	22	N(7.7; 2.2)
Product_2	23	N(4.1; 1.2)
Product_2	24	N(6.4; 1.2)

Product	Machine	Distribution (min)
Product_2	25	N(5.5; 2.2)
Product_2	26	N(6.1; 2.4)
Product_2	27	N(1.6; 0.5)
Product_2	28	N(2.4; 1.2)
Product_2	29	N(5; 1.8)
Product_2	30	N(2.8; 0.9)
Product_3	4	N(5.8; 1.8)
Product_3	5	N(6.1; 2)
Product_3	6	N(3; 1.1)
Product_3	10	N(4.4; 0.9)
Product_3	11	N(2.9; 1)
Product_3	15	N(3.3; 1.6)
Product_3	16	N(2; 1)
Product_3	17	N(5.6; 1.2)
Product_3	18	N(6.7; 2.1)
Product_3	20	N(7.1; 3)
Product_3	23	N(8.7; 3.4)
Product_3	26	N(4.9; 1.4)
Product_3	27	N(2.1; 1.1)
Product_3	28	N(3.3; 1.8)
Product_3	29	N(5.9; 1.3)
Product_3	30	N(3.3; 0.9)
Product_4	12	N(2.2; 0.6)
Product_4	15	N(9.1; 2.8)
Product_4	16	N(8.8; 1.3)
Product_4	19	N(4; 1.8)
Product_4	22	N(3.9; 1.7)
Product_4	23	N(6.4; 2.1)
Product_4	24	N(3.8; 1.1)
Product_4	28	N(2.7; 0.4)

C. (continued)

Product	Machine	Distribution (min)	Product	Machine	Distribution (min)
Product_4	29	N(3.7; 1)	Product_7	7	N(7.4; 1)
Product_4	30	N(4.7; 2.1)	Product_7	8	N(8.8; 4.1)
Product_5	1	N(5.7; 2)	Product_7	9	N(2.1; 0.4)
Product_5	2	N(3.7; 2)	Product_7	10	N(4.2; 1.2)
Product_5	3	N(8; 3)	Product_7	11	N(1.5; 0.6)
Product_5	4	N(9.7; 3.1)	Product_7	12	N(2.3; 0.9)
Product_5	5	N(7; 2)	Product_7	15	N(1.9; 0.4)
Product_5	6	N(2; 0.8)	Product_7	16	N(2.7; 0.8)
Product_5	7	N(6.7; 2.5)	Product_7	17	N(6.6; 2.3)
Product_5	8	N(5.5; 1.4)	Product_7	19	N(6.7; 1.1)
Product_5	9	N(10.4; 3.3)	Product_7	25	N(3.7; 2.4)
Product_5	12	N(1.8; 0.2)	Product_7	26	N(7.1; 1.7)
Product_5	14	N(11.2; 2.9)	Product_7	27	N(3.4; 1.3)
Product_5	15	N(5.1; 1.2)	Product_7	29	N(6.7; 2)
Product_5	16	N(4.8; 1.6)	Product_7	30	N(1.7; 0.7)
Product_5	17	N(3.1; 1)	Product_8	8	N(6; 1.5)
Product_5	18	N(6.4; 2.8)	Product_8	9	N(3.5; 0.5)
Product_6	2	N(8.4; 3.1)	Product_8	1	N(6.8; 2.5)
Product_6	3	N(2.7; 1.2)	Product_8	2	N(1.7; 0.4)
Product_6	5	N(4.8; 2.1)	Product_8	3	N(4.3; 1.3)
Product_6	6	N(3.3; 0.3)	Product_8	12	N(6.4; 1.6)
Product_6	7	N(9.8; 3.1)	Product_8	16	N(7.2; 1.8)
Product_6	8	N(6.5; 1.5)	Product_8	17	N(3.2; 1)
Product_6	9	N(2.5; 0.5)	Product_8	18	N(2.1; 0.8)
Product_6	10	N(5.5; 1.4)	Product_8	19	N(4.4; 1.2)
Product_6	11	N(6.4; 2.1)	Product_8	24	N(2.6; 0.8)
Product_6	19	N(7.4; 2.3)	Product_8	25	N(6.8; 2.1)
Product_6	30	N(9.1; 3.1)	Product_8	30	N(5; 1.5)
Product_7	5	N(8.2; 2.1)	Product_9	12	N(3; 0.5)
Product_7	6	N(5.1; 1.6)	Product_9	13	N(3.3; 1.5)

C. (continued)

Product	Machine	Distribution (min)	Product	Machine	Distribution (min)
Product_9	16	N(6.4; 2.5)	Product_12	1	N(4; 0.7)
Product_9	24	N(2.8; 1.1)	Product_12	2	N(4.6; 1)
Product_9	25	N(5.7; 1.7)	Product_12	3	N(8.1; 1.7)
Product_9	30	N(3.8; 1.3)	Product_12	10	N(6; 2.2)
Product_10	1	N(3.4; 1.7)	Product_12	11	N(9.4; 3.1)
Product_10	2	N(4.5; 0.7)	Product_12	12	N(6.5; 1.5)
Product_10	3	N(5; 1)	Product_12	13	N(4.1; 1.2)
Product_10	4	N(6.5; 2.1)	Product_12	14	N(6.5; 1.6)
Product_10	8	N(6.2; 1.1)	Product_12	15	N(7; 2.1)
Product_10	9	N(8.5; 2)	Product_12	16	N(7.6; 3)
Product_10	15	N(9; 3)	Product_12	17	N(3.9; 1.2)
Product_10	16	N(9.5; 2.5)	Product_12	18	N(2.8; 0.5)
Product_10	24	N(2.7; 1.7)	Product_13	1	N(3; 1.1)
Product_10	28	N(4.4; 1.4)	Product_13	4	N(2; 1)
Product_11	1	N(6.5; 2.7)	Product_13	6	N(3.9; 0.8)
Product_11	2	N(1.4; 0.7)	Product_13	8	N(6.8; 1.8)
Product_11	3	N(2.1; 1)	Product_13	9	N(7.2; 2.4)
Product_11	4	N(1; 0.3)	Product_13	12	N(6.2; 1.1)
Product_11	11	N(5.5; 1.7)	Product_13	16	N(3.8; 1.2)
Product_11	12	N(6; 1)	Product_13	15	N(5.5; 1.3)
Product_11	13	N(7; 2)	Product_13	18	N(5.9; 1.9)
Product_11	14	N(8.4; 2.9)	Product_13	21	N(8.2; 2.9)
Product_11	21	N(3.4; 1.2)	Product_13	22	N(8.8; 3.2)
Product_11	22	N(3.5; 2.1)	Product_13	25	N(5; 2)
Product_11	23	N(7.7; 0.9)	Product_13	27	N(8; 2)
Product_11	24	N(6.8; 2.2)	Product_14	3	N(7; 2.8)
Product_11	27	N(10.5; 4)	Product_14	4	N(7.6; 3.1)
Product_11	28	N(4.9; 2.1)	Product_14	5	N(3.9; 1)
Product_11	29	N(2.6; 0.8)	Product_14	6	N(6; 1)
Product_11	30	N(6; 1.9)	Product_14	7	N(6.4; 2)

C. (continued)

Product	Machine	Distribution (min)
Product_14	12	N(6.8; 1.8)
Product_14	19	N(5.5; 0.8)
Product_14	20	N(2.8; 0.6)
Product_14	25	N(3; 1.2
Product_14	27	N(6.3; 2.2
Product_14	28	N(6; 2.6)
Product_14	30	N(3.2; 1.1)
Product_15	1	N(6.7; 2.3)
Product_15	2	N(2.1; 0.99)
Product_15	3	N(10; 3)
Product_15	4	N(9.1; 1.9)
Product_15	5	N(6.2; 3.3)
Product_15	6	N(8.2; 2.2)
Product_15	7	N(1.2; 0.5)
Product_15	8	N(5.9; 0.6)
Product_15	9	N(6.9; 2.6)
Product_15	11	N(3.6; 2.1)
Product_15	12	N(1.6; 0.3)
Product_15	13	N(2.1; 1.1)
Product_15	18	N(8.6; 2.6)
Product_15	19	N(3.5; 1.5)
Product_15	26	N(8.5; 3.3)
Product_15	27	N(6; 2)
Product_15	28	N(6.9; 2.2)
Product_15	29	N(2.3; 0.6)
Product_15	30	N(5; 1.6)

Appendix D

W(Y,k) values for case study-II

D. W(Y,k) values

W(Y,k)	A	B																		C
W(1,19)	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.77
W(2,19)	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.77
W(3,19)	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.77
W(4,19)	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.77
W(5,19)	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.77
W(6,19)	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.77
W(7,19)	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.77
W(8,19)	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.77
W(9,19)	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.77
W(10,19)	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.76
W(11,19)	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.77
W(12,19)	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.77
W(13,19)	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.76
W(14,19)	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.76
W(15,19)	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.77

D. (continued)

W(Y,k)	A	B																		C
W(17,19)	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.76
W(18,19)	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.77
W(19,19)	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.77
W(20,19)	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.76
W(21,19)	0.01	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.75
W(22,19)	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.76
W(23,19)	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.75
W(24,19)	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.76
W(25,19)	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.77
W(26,19)	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.75
W(27,19)	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.77
W(28,19)	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.77
W(29,19)	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.77
W(30,19)	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.77

A	B	C
$\sum_{i_j \in Y} w_j$	$\sum_{i_j \in Y}^{k-q} w_{r_j}$	$W(Y,k) = \sum_{i_j \in Y} w_j + \sum_{i_j \in Y}^{k-q} w_{r_j}$

Appendix E

Calculated W(Y,k) values for case study-II

E. W(Y,k) values

B(Y,k)	wminsup	T	wminsup * T	W(Y,k)	B(Y,k) = (wminsup* T) / W(Y,k)
B(1,19)	0.2	15	3	0.765	3.924~ 4
B(2,19)	0.2	15	3	0.765	3.924~ 4
B(3,19)	0.2	15	3	0.765	3.924~ 4
B(4,19)	0.2	15	3	0.765	3.924~ 4
B(5,19)	0.2	15	3	0.765	3.924~ 4
B(6,19)	0.2	15	3	0.765	3.924~ 4
B(7,19)	0.2	15	3	0.765	3.924~ 4
B(8,19)	0.2	15	3	0.765	3.924~ 4
B(9,19)	0.2	15	3	0.765	3.924~ 4
B(10,19)	0.2	15	3	0.760	3.948~ 4
B(11,19)	0.2	15	3	0.765	3.924~ 4
B(12,19)	0.2	15	3	0.765	3.924~ 4
B(13,19)	0.2	15	3	0.758	3.958~ 4
B(14,19)	0.2	15	3	0.759	3.953~ 4
B(15,19)	0.2	15	3	0.765	3.924~ 4
B(16,19)	0.2	15	3	0.765	3.924~ 4
B(17,19)	0.2	15	3	0.761	3.942~ 4
B(18,19)	0.2	15	3	0.765	3.924~ 4
B(19,19)	0.2	15	3	0.765	3.924~ 4
B(20,19)	0.2	15	3	0.757	3.965~ 4
B(21,19)	0.2	15	3	0.750	4.001~ 5
B(22,19)	0.2	15	3	0.755	3.975~ 4
B(23,19)	0.2	15	3	0.753	3.986~ 4
B(24,19)	0.2	15	3	0.760	3.949~ 4
B(25,19)	0.2	15	3	0.765	3.924~ 4
B(26,19)	0.2	15	3	0.752	3.987~ 4
B(27,19)	0.2	15	3	0.765	3.924~ 4
B(28,19)	0.2	15	3	0.765	3.924~ 4
B(29,19)	0.2	15	3	0.765	3.924~ 4
B(30,19)	0.2	15	3	0.765	3.924~ 4

Appendix F

W(Y,k) Values for 1-level machinesets

F. W(Y,k) for 2-level machinesets

W(Y,k)	A		B																	C
W((2,3), 19)	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.77
W((1,2), 19)	0.05	0.04	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.77
W((8,9) , 19)	0.04	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.77
W((15,16) , 19)	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.77
W((29,30) , 19)	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.77
W((3,4) , 19)	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.77
W((5,6) , 19)	0.04	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.77
W((10,11) , 19)	0.02	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.76
W((28,29) , 19)	0.04	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.77
W((4,5) , 19)	0.05	0.04	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.77
W((6,7) , 19)	0.04	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.77
W((16,17) , 19)	0.05	0.03	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.76
W((27,28) , 19)	0.03	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.77
W((7,8) , 19)	0.03	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.77
W((9,10) , 19)	0.04	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.76

F. (continued)

W(Y,k)	A		B																	C
W((11,12) , 19)	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.77
W((12,13) , 19)	0.05	0.02	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.76
W((17,18) , 19)	0.03	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.76
W((26,27) , 19)	0.02	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.75
W((13,14) , 19)	0.02	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.75
W((14,15) , 19)	0.02	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.76
W((22,23) , 19)	0.02	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.74
W((23,24) , 19)	0.02	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.75
W((24,25) , 19)	0.02	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.76
W((9,12) , 19)	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.77
W((12,15) , 19)	0.05	0.04	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.77
W((12,16) , 19)	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.77
W((16,24) , 19)	0.05	0.02	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.76
W((18,19) , 19)	0.03	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.77
W((19,20) , 19)	0.03	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.76

F. (continued)

W(Y,k)	A		B																	C
W((24,28) , 19)	0.02	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.76
W((25,26) , 19)	0.03	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.75
W((25,27) , 19)	0.03	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.77
W((25,30) , 19)	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.77
W((1,4) , 19)	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.77
W((1,9) , 19)	0.05	0.04	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.77
W((3,9) , 19)	0.05	0.04	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.77
W((3,5) , 19)	0.05	0.04	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.77
W((3,12) , 19)	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.77
W((3,10) , 19)	0.05	0.02	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.76
W((4,8) , 19)	0.05	0.04	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.77
W((4,11) , 19)	0.05	0.03	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.77
W((4,6) , 19)	0.05	0.04	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.77
W((5,8) , 19)	0.04	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.77
W((6,10) , 19)	0.04	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.76
W((6,8) , 19)	0.04	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.77

F. (continued)

W(Y,k)	A		B																	C
W((7,12) , 19)	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.77
W((8,11) , 19)	0.04	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.77
W((8,19) , 19)	0.04	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.77
W((9,15) , 19)	0.04	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.77
W((9,11) , 19)	0.04	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.77
W((11,13) , 19)	0.03	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.76
W((11,15) , 19)	0.03	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.77
W((11,19) , 19)	0.03	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.77
W((12,14) , 19)	0.05	0.02	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.76
W((12,19) , 19)	0.05	0.03	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.77
W((13,16) , 19)	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.76
W((13,18) , 19)	0.02	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.76
W((15,18) , 19)	0.04	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.77
W((16,20) , 19)	0.05	0.02	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.76
W((16,19) , 19)	0.05	0.03	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.77

F. (continued)

W(Y,k)	A		B																	C
W((17,19) , 19)	0.03	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.76
W((18,20) , 19)	0.03	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.75
W((19,30) , 19)	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.77
W((19,25) , 19)	0.03	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.77
W((19,24) , 19)	0.03	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.76
W((19,26) , 19)	0.03	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.75
W((20,25) , 19)	0.02	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.76
W((20,28) , 19)	0.02	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.76
W((22,25) , 19)	0.02	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.75
W((20,23) , 19)	0.02	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.74
W((23,26) , 19)	0.02	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.74
W((24,27) , 19)	0.02	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.76
W((27,29) , 19)	0.03	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.77
W((28,30) , 19)	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.77
W((19,22) , 19)	0.03	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.76

A	B	C
$\sum_{i_j \in Y} w_j$	$\sum_{i_j \in Y}^{k-q} w_{r_j}$	$W(Y,k) = \sum_{i_j \in Y} w_j + \sum_{i_j \in Y}^{k-q} w_{r_j}$

Appendix G

B(Y,k) values for 1-level machinesets

G. B(Y,k) values

B(Y,k)	wminsup	T	Wminsup* T	B(Y,k)	B(Y,k) = (wminsup *T) / B(Y,k)
B((2,3) , 19)	0.2	15	3	0.765	3.924~ 4
B((1,2) , 19)	0.2	15	3	0.765	3.924~ 4
B((8,9) , 19)	0.2	15	3	0.765	3.924~ 4
B((15,16) , 19)	0.2	15	3	0.765	3.924~ 4
B((29,30) , 19)	0.2	15	3	0.765	3.924~ 4
B((3,4) , 19)	0.2	15	3	0.765	3.924~ 4
B((5,6) , 19)	0.2	15	3	0.765	3.924~ 4
B((10,11) , 19)	0.2	15	3	0.760	3.948~ 4
B((28,29) , 19)	0.2	15	3	0.765	3.924~ 4
B((4,5) , 19)	0.2	15	3	0.765	3.924~ 4
B((6,7) , 19)	0.2	15	3	0.765	3.924~ 4
B((16,17) , 19)	0.2	15	3	0.761	3.942~ 4
B((27,28) , 19)	0.2	15	3	0.765	3.924~ 4
B((7,8) , 19)	0.2	15	3	0.765	3.924~ 4
B((9,10) , 19)	0.2	15	3	0.760	3.948~ 4
B((11,12) , 19)	0.2	15	3	0.765	3.924~ 4
B((12,13) , 19)	0.2	15	3	0.758	3.958~ 4
B((17,18) , 19)	0.2	15	3	0.761	3.942~ 4
B((26,27) , 19)	0.2	15	3	0.752	3.987~ 4
B((13,14) , 19)	0.2	15	3	0.751	3.994~ 4
B((14,15) , 19)	0.2	15	3	0.759	3.953~ 4
B((22,23) , 19)	0.2	15	3	0.742	4.046~ 5
B((23,24) , 19)	0.2	15	3	0.747	4.018~ 5
B((24,25) , 19)	0.2	15	3	0.759	3.955~ 4
B((9,12) , 19)	0.2	15	3	0.765	3.924~ 4
B((12,15) , 19)	0.2	15	3	0.765	3.924~ 4
B((12,16) , 19)	0.2	15	3	0.765	3.924~ 4
B((16,24) , 19)	0.2	15	3	0.760	3.949~ 4
B((18,19) , 19)	0.2	15	3	0.765	3.924~ 4
B((19,20) , 19)	0.2	15	3	0.757	3.965~ 4
B((24,28) , 19)	0.2	15	3	0.760	3.949~ 4
B((25,26) , 19)	0.2	15	3	0.751	3.993~ 4
B((25,27) , 19)	0.2	15	3	0.765	3.924~ 4
B((25,30) , 19)	0.2	15	3	0.765	3.924~ 4
B((1,4) , 19)	0.2	15	3	0.765	3.924~ 4
B((1,9) , 19)	0.2	15	3	0.765	3.924~ 4
B((3,9) , 19)	0.2	15	3	0.765	3.924~ 4
B((3,5) , 19)	0.2	15	3	0.765	3.924~ 4
B((3,12) , 19)	0.2	15	3	0.765	3.924~ 4

G. (continued)

B(Y,k)	wminsup	T	Wminsup* T	B(Y,k)	B(Y,k) = (wminsup *T) / B(Y,k)
B((3,10) , 19)	0.2	15	3	0.760	3.948~ 4
B((4,8) , 19)	0.2	15	3	0.765	3.924~ 4
B((4,11) , 19)	0.2	15	3	0.765	3.924~ 4
B((4,6) , 19)	0.2	15	3	0.765	3.924~ 4
B((5,8) , 19)	0.2	15	3	0.765	3.924~ 4
B((6,10) , 19)	0.2	15	3	0.760	3.948~ 4
B((6,8) , 19)	0.2	15	3	0.765	3.924~ 4
B((7,12) , 19)	0.2	15	3	0.765	3.924~ 4
B((8,11) , 19)	0.2	15	3	0.765	3.924~ 4
B((8,19) , 19)	0.2	15	3	0.765	3.924~ 4
B((9,15) , 19)	0.2	15	3	0.765	3.924~ 4
B((9,11) , 19)	0.2	15	3	0.765	3.924~ 4
B((11,13),19)	0.2	15	3	0.758	3.958~ 4
B((11,15) , 19)	0.2	15	3	0.765	3.924~ 4
B((11,19) , 19)	0.2	15	3	0.765	3.924~ 4
B((12,14) , 19)	0.2	15	3	0.759	3.953~ 4
B((12,19) , 19)	0.2	15	3	0.765	3.924~ 4
B((13,16) , 19)	0.2	15	3	0.758	3.958~ 4
B((13,18) , 19)	0.2	15	3	0.758	3.958~ 4
B((15,18) , 19)	0.2	15	3	0.765	3.924~ 4
B((16,20) , 19)	0.2	15	3	0.757	3.965~ 4
B((16,19) , 19)	0.2	15	3	0.765	3.924~ 4
B((17,19) , 19)	0.2	15	3	0.761	3.942~ 4
B((18,20) , 19)	0.2	15	3	0.754	3.978~ 4
B((19,30) , 19)	0.2	15	3	0.765	3.924~ 4
B((19,25) , 19)	0.2	15	3	0.765	3.924~ 4
B((19,24) , 19)	0.2	15	3	0.760	3.949~ 4
B((19,26) , 19)	0.2	15	3	0.752	3.987~ 4
B((20,25) , 19)	0.2	15	3	0.755	3.971~ 4
B((20,28) , 19)	0.2	15	3	0.757	3.965~ 4
B((22,25) , 19)	0.2	15	3	0.753	3.982~ 4
B((20,23) , 19)	0.2	15	3	0.744	4.035~ 5
B((23,26) , 19)	0.2	15	3	0.739	4.057~ 5
B((24,27) , 19)	0.2	15	3	0.760	3.949~ 4
B((27,29) , 19)	0.2	15	3	0.765	3.924~ 4
B((28,30) , 19)	0.2	15	3	0.765	3.924~ 4
B((19,22) , 19)	0.2	15	3	0.755	3.975~ 4

Appendix H

The calculated weight of the products

H. Calculated weight of the product

PRODUCTS	Weight	Normalized Weight
Product_1	0.640	0.085
Product_2	0.603	0.080
Product_3	0.534	0.071
Product_4	0.346	0.046
Product_5	0.602	0.080
Product_6	0.423	0.056
Product_7	0.611	0.081
Product_8	0.515	0.068
Product_9	0.223	0.030
Product_10	0.417	0.055
Product_11	0.535	0.071
Product_12	0.448	0.059
Product_13	0.489	0.065
Product_14	0.450	0.060
Product_15	0.714	0.095
TOTAL	7.550	1

Appendix I

Sorted all machine pairs with descending order according to their weight value (List A)

I.List A

Machine Pair	Weight
{2,3}	0.649
{1,2}	0.593
{8,9}	0.584
{15,16}	0.541
{29,30}	0.528
{28,29}	0.447
{3,4}	0.445
{5,6}	0.442
{10,11}	0.432
{4,5}	0.389
{6,7}	0.371
{16,17}	0.359
{26,27}	0.326
{27,28}	0.316
{7,8}	0.311
{11,12}	0.306
{9,10}	0.302
{17,18}	0.278
{12,13}	0.254
{14,15}	0.224
{21,22}	0.216
{13,14}	0.215
{22,23}	0.197
{23,24}	0.197
{24,25}	0.178
{19,26}	0.174
{18,19}	0.163
{25,26}	0.161
{9,12}	0.145
{19,20}	0.140
{12,16}	0.133
{12,15}	0.127
{25,27}	0.124
{24,28}	0.101
{25,30}	0.098
{9,11}	0.095
{13,18}	0.095
{5,8}	0.085
{11,13}	0.085
{16,20}	0.085

Machine Pair	Weight
{20,28}	0.085
{16,24}	0.085
{17,19}	0.081
{19,25}	0.081
{27,29}	0.081
{3,9}	0.080
{8,11}	0.080
{8,19}	0.080
{20,21}	0.080
{12,14}	0.080
{4,11}	0.071
{14,21}	0.071
{24,27}	0.071
{6,10}	0.071
{11,15}	0.071
{18,20}	0.071
{20,23}	0.071
{23,26}	0.071
{1,9}	0.068
{3,12}	0.068
{19,24}	0.068
{1,4}	0.065
{4,6}	0.065
{6,8}	0.065
{15,18}	0.065
{18,21}	0.065
{22,25}	0.065
{7,12}	0.060
{12,19}	0.060
{20,25}	0.060
{28,30}	0.060
{3,10}	0.059
{3,5}	0.056
{11,19}	0.056
{19,30}	0.056
{4,8}	0.055
{9,15}	0.055
{16,19}	0.046
{19,22}	0.046
{13,16}	0.030

Appendix J

The calculated WS(X) values for each machine pair (List A)

J. WS(X) values

Machine Pair	WS(X) value
{2,3}	0.0013125
{15,16}	0.0011059
{1,2}	0.0010602
{8,9}	0.0010377
{3,4}	0.0007987
{29,30}	0.0006966
{5,6}	0.0006053
{4,5}	0.0005020
{11,12}	0.0004740
{28,29}	0.0004705
{27,28}	0.0004436
{16,17}	0.0004252
{6,7}	0.0003859
{12,16}	0.0003523
{7,8}	0.0003448
{10,11}	0.0003271
{12,13}	0.0003212
{9,12}	0.0003139
{12,15}	0.0002980
{9,10}	0.0002888
{17,18}	0.0002301
{14,15}	0.0001969
{25,30}	0.0001912
{3,12}	0.0001807
{26,27}	0.0001567
{3,9}	0.0001494
{1,9}	0.0001357
{25,27}	0.0001351
{3,5}	0.0001297
{16,24}	0.0001288
{28,30}	0.0001256
{9,15}	0.0001231
{1,4}	0.0001210
{18,19}	0.0001207
{6,8}	0.0001161
{4,8}	0.0001156
{5,8}	0.0001127
{13,14}	0.0001061
{7,12}	0.0001043
{4,6}	0.0001035
{24,28}	0.0001002
{8,11}	0.0000979
{9,11}	0.0000979
{12,19}	0.0000962
{15,18}	0.0000935
{11,15}	0.0000930
{16,19}	0.0000892
{19,30}	0.0000881
{4,11}	0.0000873
{12,14}	0.0000836
{3,10}	0.0000831
{8,19}	0.0000795
{19,20}	0.0000765
{13,16}	0.0000745
{27,29}	0.0000703
{16,20}	0.0000701
{23,24}	0.0000673
{25,26}	0.0000665
{24,25}	0.0000664
{22,23}	0.0000662
{6,10}	0.0000646
{11,19}	0.0000600
{21,22}	0.0000550
{20,28}	0.0000545
{19,25}	0.0000529
{13,18}	0.0000504
{11,13}	0.0000501
{18,20}	0.0000474
{17,19}	0.0000464
{24,27}	0.0000449
{20,25}	0.0000415
{22,25}	0.0000376
{19,22}	0.0000346
{19,24}	0.0000330
{18,21}	0.0000320
{19,26}	0.0000306
{20,23}	0.0000244
{14,21}	0.0000224
{20,21}	0.0000203
{23,26}	0.0000195

Appendix K

NWS values for case study-II

K. NWS values

Machine	Weight	Support Count (SC)	Number of product(T)	SC/T	Weight*(SC/T)(NWS)
{1}	0.046	9	15	0.600	0.028
{2}	0.043	9	15	0.600	0.026
{3}	0.051	10	15	0.667	0.034
{4}	0.039	8	15	0.533	0.021
{5}	0.038	7	15	0.467	0.018
{6}	0.039	7	15	0.467	0.018
{7}	0.029	5	15	0.333	0.010
{8}	0.044	9	15	0.600	0.026
{9}	0.044	9	15	0.600	0.026
{10}	0.025	6	15	0.400	0.010
{11}	0.033	8	15	0.533	0.018
{12}	0.053	10	15	0.667	0.036
{13}	0.023	5	15	0.333	0.008
{14}	0.024	4	15	0.267	0.006
{15}	0.042	8	15	0.533	0.022
{16}	0.050	10	15	0.667	0.033
{17}	0.026	5	15	0.333	0.009
{18}	0.033	6	15	0.400	0.013
{19}	0.027	7	15	0.467	0.013
{20}	0.021	4	15	0.267	0.006
{21}	0.014	3	15	0.200	0.003
{22}	0.019	4	15	0.267	0.005
{23}	0.017	4	15	0.267	0.005
{24}	0.020	6	15	0.400	0.008
{25}	0.029	6	15	0.400	0.012
{26}	0.017	4	15	0.267	0.005
{27}	0.035	7	15	0.467	0.016
{28}	0.039	8	15	0.533	0.021
{29}	0.031	7	15	0.467	0.014
{30}	0.049	11	15	0.733	0.036

Appendix L

2-level Machinesets for case study-II

L. 2-level Machinesets

Machine Pair(a+b)	Weight (a+b)	Y= ((a+b)/2)	Support Count (SC)	Number of product(T)	X=SC/T	NWS=X*Y
{1,2}	0.0892	0.0446	8	15	0.5333	0.0238
{1,4}	0.0855	0.0427	1	15	0.0667	0.0028
{1,9}	0.0903	0.0451	1	15	0.0667	0.0030
{2,3}	0.0939	0.0469	9	15	0.6000	0.0282
{3,4}	0.0901	0.0451	6	15	0.4000	0.0180
{3,9}	0.0949	0.0475	1	15	0.0667	0.0032
{3,5}	0.0891	0.0446	1	15	0.0667	0.0030
{3,12}	0.1042	0.0521	1	15	0.0667	0.0035
{3,10}	0.0753	0.0377	1	15	0.0667	0.0025
{4,5}	0.0776	0.0388	5	15	0.3333	0.0129
{4,8}	0.0834	0.0417	1	15	0.0667	0.0028
{4,11}	0.0726	0.0363	1	15	0.0667	0.0024
{4,6}	0.0788	0.0394	1	15	0.0667	0.0026
{5,8}	0.0824	0.0412	1	15	0.0667	0.0027
{5,6}	0.0778	0.0389	6	15	0.4000	0.0156
{6,10}	0.0640	0.0320	1	15	0.0667	0.0021
{6,7}	0.0688	0.0344	5	15	0.3333	0.0115
{6,8}	0.0836	0.0418	1	15	0.0667	0.0028
{7,8}	0.0734	0.0367	4	15	0.2667	0.0098
{7,12}	0.0827	0.0413	1	15	0.0667	0.0028
{8,9}	0.0882	0.0441	8	15	0.5333	0.0235
{8,11}	0.0774	0.0387	1	15	0.0667	0.0026
{8,19}	0.0711	0.0356	1	15	0.0667	0.0024
{9,10}	0.0687	0.0343	4	15	0.2667	0.0092
{9,12}	0.0975	0.0487	2	15	0.1333	0.0065
{9,15}	0.0860	0.0430	1	15	0.0667	0.0029
{9,11}	0.0774	0.0387	1	15	0.0667	0.0026
{10,11}	0.0579	0.0289	6	15	0.4000	0.0116
{11,15}	0.0752	0.0376	1	15	0.0667	0.0025
{11,19}	0.0603	0.0302	1	15	0.0667	0.0020
{11,12}	0.0867	0.0433	4	15	0.2667	0.0116
{12,15}	0.0952	0.0476	2	15	0.1333	0.0063
{12,14}	0.0769	0.0384	1	15	0.0667	0.0026
{12,16}	0.1029	0.0514	2	15	0.1333	0.0069
{12,13}	0.0012	0.0006	4	15	0.2667	0.0002
{12,19}	0.0804	0.0402	1	15	0.0667	0.0027
{13,14}	0.0461	0.0230	3	15	0.2000	0.0046
{13,16}	0.0721	0.0360	1	15	0.0667	0.0024

L.(continued)

Machine Pair(a+b)	Weight (a+b)	Y= ((a+b)/2)	Support Count (SC)	Number of product(T)	X=SC/T	NWS=X*Y
{13,18}	0.0561	0.0280	1	15	0.0667	0.0019
{14,15}	0.0654	0.0327	3	15	0.2000	0.0065
{15,16}	0.0914	0.0457	8	15	0.5333	0.0244
{15,18}	0.0754	0.0377	1	15	0.0667	0.0025
{16,20}	0.0707	0.0354	1	15	0.0667	0.0024
{16,17}	0.0753	0.0376	5	15	0.3333	0.0125
{16,19}	0.0765	0.0383	1	15	0.0667	0.0026
{16,24}	0.0690	0.0345	2	15	0.1333	0.0046
{17,18}	0.0593	0.0296	4	15	0.2667	0.0079
{17,19}	0.0528	0.0264	1	15	0.0667	0.0018
{18,20}	0.0547	0.0274	1	15	0.0667	0.0018
{18,19}	0.0605	0.0303	2	15	0.1333	0.0040
{19,20}	0.0483	0.0241	2	15	0.1333	0.0032
{19,30}	0.0013	0.0007	1	15	0.0667	0.0000
{19,25}	0.0564	0.0282	1	15	0.0667	0.0019
{19,24}	0.0465	0.0233	1	15	0.0667	0.0016
{19,26}	0.0440	0.0220	1	15	0.0667	0.0015
{18,21}	0.0478	0.0239	1	15	0.0667	0.0016
{20,25}	0.0506	0.0253	1	15	0.0667	0.0017
{20,28}	0.0598	0.0299	1	15	0.0667	0.0020
{22,25}	0.0486	0.0243	1	15	0.0667	0.0016
{24,25}	0.0365	0.0183	3	15	0.2000	0.0037
{24,27}	0.0541	0.0270	1	15	0.0667	0.0018
{24,28}	0.0580	0.0290	2	15	0.1333	0.0039
{25,26}	0.0463	0.0232	2	15	0.1333	0.0031
{25,27}	0.0639	0.0319	2	15	0.1333	0.0043
{25,30}	0.0782	0.0391	2	15	0.1333	0.0052
{26,27}	0.0516	0.0258	4	15	0.2667	0.0069
{27,28}	0.0731	0.0365	5	15	0.3333	0.0122
{27,29}	0.0651	0.0325	1	15	0.0667	0.0022
{28,29}	0.0691	0.0345	6	15	0.4000	0.0138
{28,30}	0.0874	0.0437	1	15	0.0667	0.0029
{29,30}	0.0794	0.0397	7	15	0.4667	0.0185
{19,22}	0.0462	0.0231	1	15	0.0667	0.0015

Appendix M

3-level machinesets for case study-II

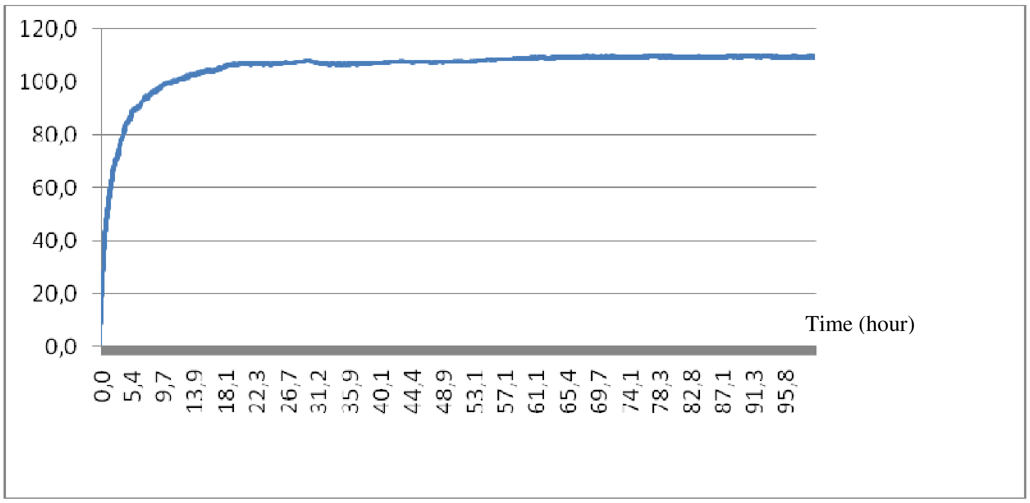
M. 3-level machinesets

Machine Pair(a+b+c)	Weight (a+b+c)	Y= ((a+b)/3)	Support Count (SC)	Number of product(T)	X=SC/T	NWS=X*Y
{2,3,4}	0.1332	0.0444	5	15	0.3333	0.0148
{2,3,5}	0.1322	0.0441	1	15	0.0667	0.0029
{2,3,10}	0.1184	0.0395	1	15	0.0667	0.0026
{14,15,16}	0.1149	0.0383	3	15	0.2000	0.0077
{15,16,20}	0.1126	0.0375	1	15	0.0667	0.0025
{11,15,16}	0.1247	0.0416	1	15	0.0667	0.0028
{15,16,17}	0.1172	0.0391	3	15	0.2000	0.0078
{15,16,19}	0.1184	0.0395	1	15	0.0667	0.0026
{15,16,24}	0.1109	0.0370	1	15	0.0667	0.0025
{15,16,18}	0.1249	0.0416	1	15	0.0667	0.0028
{3,4,5}	0.1284	0.0428	4	15	0.2667	0.0114
{3,4,11}	0.1234	0.0411	1	15	0.0667	0.0027
{5,6,7}	0.1071	0.0357	5	15	0.3333	0.0119
{5,6,10}	0.1024	0.0341	1	15	0.0667	0.0023
{20,28,29}	0.0903	0.0301	1	15	0.0667	0.0020
{24,28,29}	0.0886	0.0295	1	15	0.0667	0.0020
{26,27,28}	0.0901	0.0300	3	15	0.2000	0.0060
{27,28,29}	0.1036	0.0345	4	15	0.2667	0.0092
{24,27,28}	0.0926	0.0309	1	15	0.0667	0.0021
{25,27,28}	0.1024	0.0341	1	15	0.0667	0.0023
{5,8,9}	0.1265	0.0422	1	15	0.0667	0.0028
{8,9,10}	0.1128	0.0376	3	15	0.2000	0.0075
{7,8,9}	0.1175	0.0392	4	15	0.2667	0.0104
{4,8,9}	0.1275	0.0425	1	15	0.0667	0.0028
{8,9,15}	0.1301	0.0434	1	15	0.0667	0.0029
{6,8,9}	0.1277	0.0426	1	15	0.0667	0.0028
{8,9,11}	0.1215	0.0405	1	15	0.0667	0.0027

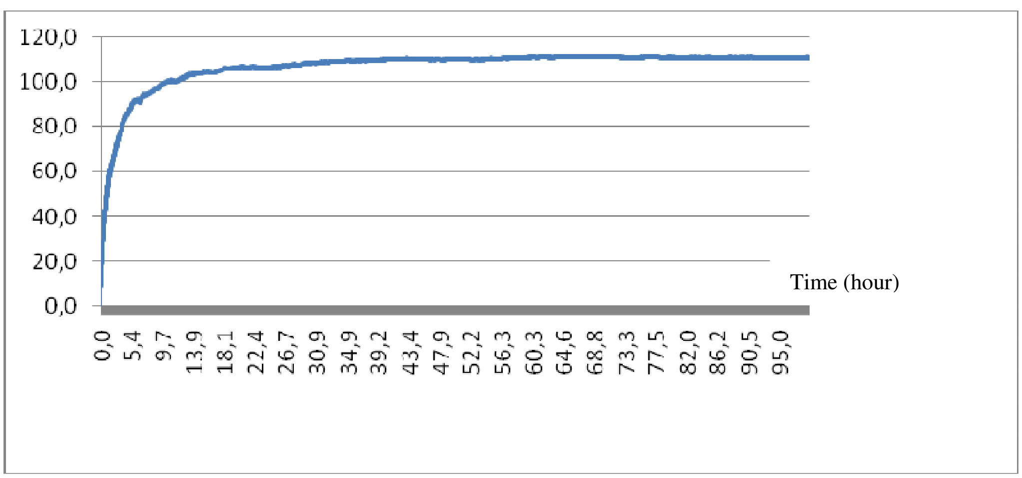
Appendix N

The amount of product produced per unit time corresponding to different layouts for case study-II

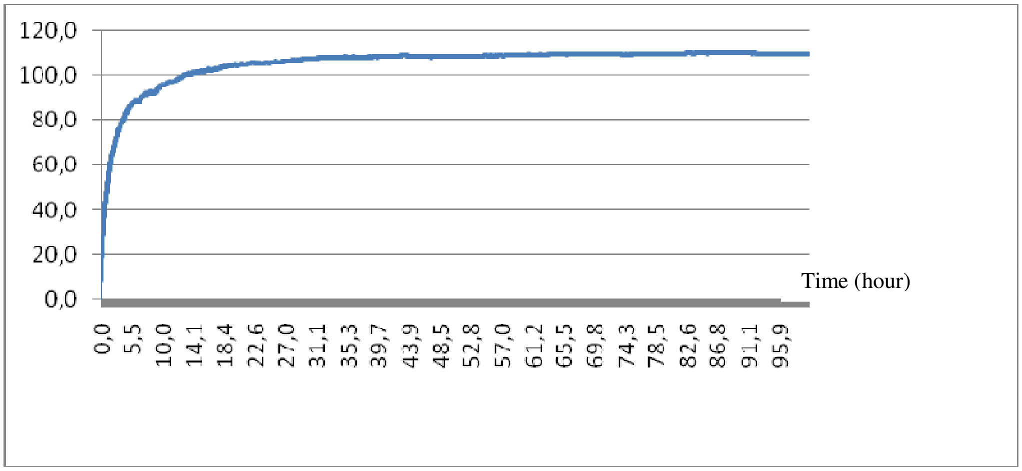
N1. The amount of product corresponding to layout 1



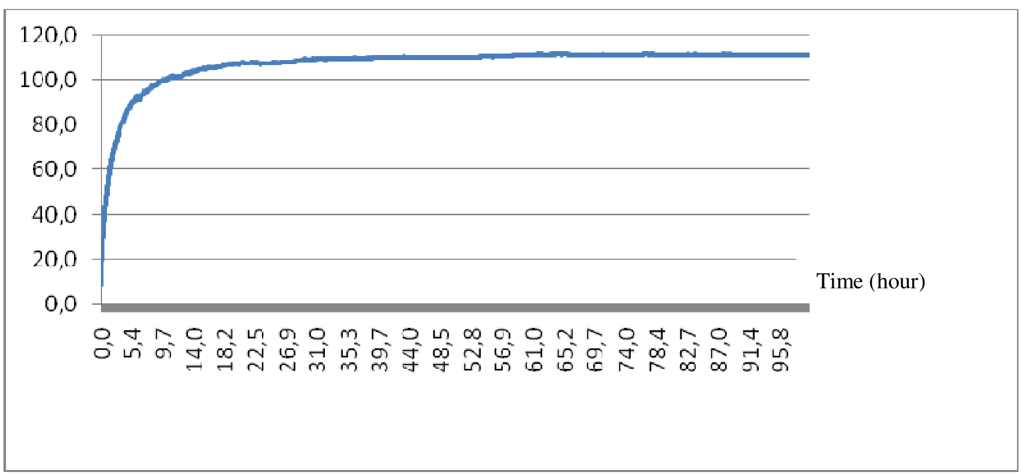
N2. The amount of product corresponding to layout 2



N3. The amount of product corresponding to layout 3.



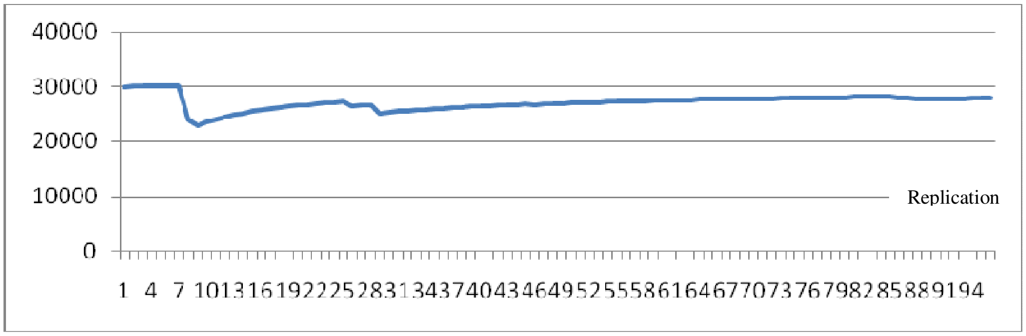
N4. The amount of product corresponding to layout 4



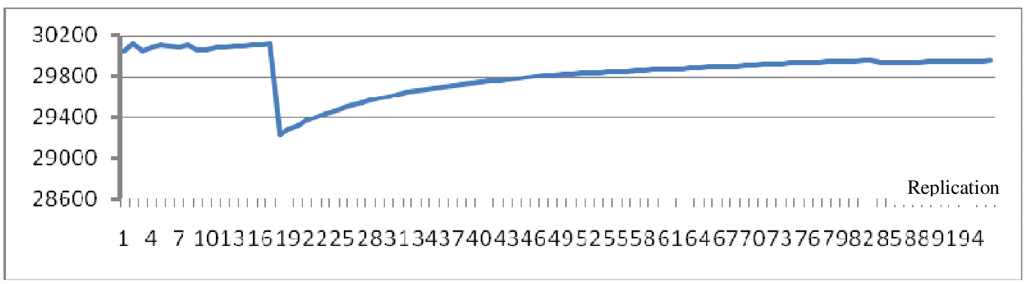
Appendix P

Moving averages of the amount of production for each replication corresponding to different layouts for case study-II

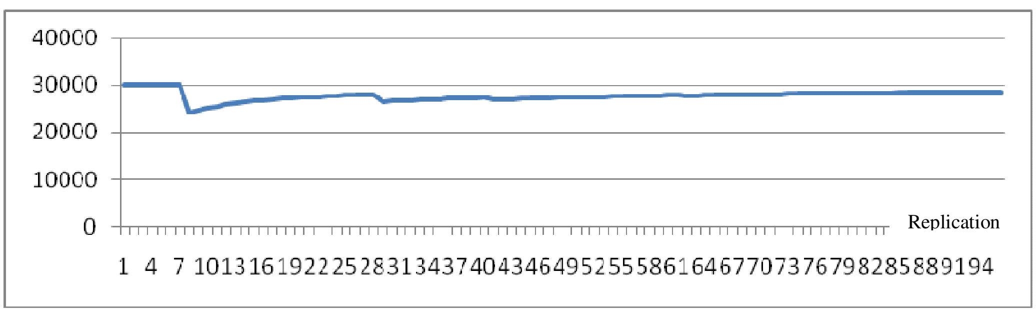
P1 Moving averages of the amount of production corresponding to layout 1



P2. Moving averages of the amount of production corresponding to layout 2



P3. Moving averages of the amount of production corresponding to layout 3



P4. Moving averages of the amount of production corresponding to layout 4